STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES

FEATHER RIVER AND DELTA DIVERSION PROJECTS

BULLETIN NO. 78

INVESTIGATION OF ALTERNATIVE AQUEDUCT SYSTEMS TO SERVE SOUTHERN CALIFORNIA

APPENDIX C

PROCEDURE FOR ESTIMATING COSTS OF TUNNEL CONSTRUCTION

EDMUND G. BROWN
Governor

HARVEY O. BANKS
Director

September, 1959

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CHAPTER I. INTRODUCTION

During the period 1956 to 1959, the Department of Water Resources, in connection with the Feather River and Delta Diversion Projects, carried out an investigation of alternative aqueduct systems pursuant to legislative authorization and appropriation. The results of this investigation have been published in Bulletin No. 78, "Investigation of Alternative Aqueduct Systems to Serve Southern California", September, 1959.

The conduct of the investigation entailed consideration of a large number of aqueduct routes leading from the San Joaquin Valley into southern California. Because of the rugged and mountainous nature of the terrain separating the San Joaquin Valley from the south coastal area of California, all economical possibilities for such aqueduct routes would require substantial tunnel construction.

For all aqueduct routes considered, at least reconnaissance type cost estimates were needed, and, for the more promising alignments, more refined cost estimates were required. Since tunneling costs constitute a significant part of the over-all cost of aqueduct construction, and because of the unique problems inherent in estimating costs of these subsurface facilities, special consideration was given to this problem during the investigation.

This report, published as Appendix C of Bulletin No. 78, sets forth a standardized procedure for estimating tunneling costs, which procedure was utilized in all phases of the investigation of alternative aqueduct routes to southern California. Although the report was developed for the foregoing specific purpose, it is believed that the procedure outlined,

together with material and data presented herein, will be useful to engineers and geologists engaged in preparing preliminary cost estimates of tunnels in other areas.

Construction costs of tunnels are directly related to geologic conditions encountered. In the area investigated in connection with the preparation of Bulletin No. 78, the geology is very complex and includes a wide variety of rock conditions. The outlined procedure provides a method whereby the varying influence of geologic conditions on construction costs is directly reflected in the estimate.

It should be emphasized that the procedure described herein was developed primarily to provide a rapid, standardized method of estimating tunnel construction costs within the accepted limits of accuracy of a preliminary estimate by utilizing, insofar as possible, such pertinent field data that can be obtained readily. Consequently, the methods have not been used to provide exact or final costs for tunnels proposed in Bulletin No. 78. However, with the availability of better data, this procedure could be adapted for the preparation of more refined estimates of cost.

Authorization for Investigation

Statutory authorization of the Feather River and Delta Diversion Projects is contained in Division 6, Article 9.5 of the California Water Code.

This investigation was originally authorized and funds appropriated therefor by the Legislature in 1956. The Legislatures of 1957 and 1958 subsequently appropriated additional funds for continuation and completion of the investigation.

Scope of Investigation and Report

The investigation leading to the preparation of this report consisted of research of available literature on tunnel construction and compilation of records of construction progress and experience on tunneling for varying ground conditions. Rates of progress and data on underground conditions were studied for a total of 99 tunnel projects. Information compiled for tunnel cost studies was obtained from private and governmental agencies having experience in tunnel construction, from tunneling equipment manufacturers, from tunnel contractors, and from technical journals. Consideration was given to all of the major factors which influence tunnel costs.

Only tunnel projects constructed since the year 1930 were evaluated so that estimating data developed would reflect modern tunneling procedures and equipment. Cost estimating data were developed for grade or nonpressure tunnels lined to a modified horseshoe or circular section. Tunnels subjected to internal hydraulic pressures are not treated herein. Unlined bore sizes considered ranged from nine to twenty-four feet in diameter, although costs were projected for bores up to twenty-eight feet in diameter. These data were prepared for tunnel headings of up to five miles in length.

Estimating data presented herein are applicable only to tunnels driven from portal headings. Where shaft headings are needed, additional costs must be computed for shaft construction and hoisting equipment. In addition, increased costs of dewatering, ventilation, muck disposal, and electrical power that are incurred in such an operation must be taken into account. Similar additional costs are incurred where working from access

adits. Analyses of costs for headings from shafts and adits are beyond the scope of this report, and where encountered, must be handled as individual cost estimating problems.

The subject matter of this report is presented herein under the following chapter headings:

Chapter I Introduction

Chapter II Criteria for Development of Basic Tunneling Costs

Chapter III Procedure for Estimating Tunnel Costs

Following Chapter III are tables setting forth certain of the basic data utilized in development of the outlined procedure, cost estimating forms, and a bibliography. Bound at the end of the report are plates showing typical tunnel sections, rates of heading advance under various rock conditions, areas where subsistence payments are required for construction personnel in southern California, together with cost curves for tunnel excavation, steel support, timber lagging and support, and concrete lining.

Definitions

In the preparation of this report, use is made of specialized terms referring to tunnel construction work. There are presented following definitions of these terms as utilized:

A Line--That line within which no steel support or timber support will be permitted to remain, as shown on Plates 1, 2, 3, 4, and 5.

B Line--That line within which no lagging, spiling, crown bars, collar braces, spreaders, unexcavated material or tamped fill will be permitted to remain, as shown on Plates 1, 2, 3, 4, and 5.

Pay Line--The line which constitutes limits of payment for excavation and concrete lining, as shown on Plates 1, 2, 3, 4, and 5.

Overbreak--Any excavation beyond the pay line.

Overrun--Any excess concrete placed beyond the pay line.

Full Face Method of Excavation--A method in which the tunnel face is blasted out to full bore size at each drilling and blasting round. This method of excavation is used wherever possible.

Multiple Drift Method of Excavation--A method in which two small side drifts are driven along each side of tunnel allowing side support to be placed. A top drift is then driven and widened out slowly to take the roof supports. This method is used in bad tunneling ground.

Top Heading and Bench Method of Excavation--A top heading is carried approximately 1-1/2 times the length of one round ahead of the lower heading or bench. This has frequently been used in the past for tunnels of large bore size.

Top Heading Method of Excavation--Similar to top heading and bench method, but top heading is driven through as one operation followed by later removal of bench. This is used when bad roof conditions exist in tunnel.

Forepoling Method of Excavation--A method whereby timber or steel members are driven ahead of last rib. These members act as cantilevers which carry the weight of the ground until the next rib can be installed. This method is commonly used in "running ground".

Spiling--This term refers to the driving of timber or steel members ahead of the last rib or set in the method of forepoling. These members act as cantilevers which carry the weight of the ground until these forward ends are supported by installing the next rib. This is commonly used in "running ground".

Posts--Posts serve to transmit load from arch ribs to footings on the bottom of the tunnel, as shown on Plates 1 and 2.

Foot Blocks--Blocks placed for footings under ribs or posts, as shown on Plates 1 and 2.

Invert Struts--Struts which are curved in an invert arch and are placed in the subgrade to prevent inward movement of rib or post feet, as shown on Plates 1 and 2.

Lagging--Those members of a tunnel support which span the spaces between the main supporting ribs or timber sets.

CHAPTER II. CRITERIA FOR DEVELOPMENT OF BASIC TUNNELING COSTS

One of the greatest influences on tunnel costs is the type or types of ground that must be penetrated by the tunnel. For this reason, a procedure was formulated whereby preliminary estimates of tunnel costs could be developed on the basis of material classification.

As a first step in the development of this procedure, standards of ground classification were set which were designed to cover almost any possible tunneling condition. The resultant classification developed in this report contains eight conditions ranging from hard intact rock in dry headings to unconsolidated materials in wet headings.

Once standards for ground conditions were established, a study was made of the various components comprising tunnel construction costs and the variation therein with the type and conditions of the material penetrated. During the course of this study, records of construction progress and experience on 99 tunneling projects were compiled and analyzed. In the selection of these projects for study, as stated, only those tunnels constructed since the year 1930 were utilized in order that the data analyzed would reflect modern tunneling procedures. From these construction records, basic data on work progress and equipment and material requirements were compiled, and criteria established for crews and equipment needed for varying bore sizes and ground conditions.

Unit costs for personnel, equipment, and materials then were determined, using rates prevailing in January, 1957. Labor costs were obtained from the Tunnel Master Agreement of Southern California District Council of Laborers. Quoted prices obtained from manufacturers were utilized for equipment costs. Costs for water and ventilation pipe, electrical equipment, trackage, explosives, drill bits and rods were obtained from principal

suppliers of these items. Unit costs used for steel, concrete, and timbering were determined by obtaining an average unit cost of these items in prevailing bid schedules on tunnel projects. In addition to bid schedules, costs for materials, necessary processing, handling and installation plus contractor's profit were obtained. Based upon this information, unit costs for steel and timber support and concrete lining were determined and compared to unit costs of prevailing bid schedules.

From these data the basic costs of excavation were developed for a range of unlined tunnel diameters varying from nine to twenty-eight feet for eight different ground conditions. Costs for dewatering tunnel headings for varying conditions of water inflows were separately estimated. Based upon tunnel cross-section design requirements, quantities and costs were estimated for concrete lining and steel and timber support.

The foregoing data were utilized in preparing a set of curves from which estimates of tunnel construction can be obtained. The following sections contain descriptions of standards, procedures, and assumptions used in developing basic excavation costs, dewatering costs, costs of concrete lining, and costs of steel and timber support.

Standards for Ground Conditions

Ground conditions along possible tunnel alignments are ascertained by geologists and engineers in the field either by surficial examination or by subsurface exploratory drilling or by a combination of both. Ground conditions may vary widely along certain tunnel alignments and the degree of detail to which geologic exploration is carried will greatly influence the reliability of a tunnel cost estimate. Therefore, cost estimates of tunnel

construction should be based upon conservative assumptions as to subsurface conditions where information on these conditions has not been determined in detail.

In order to provide a standard for compiling basic field geologic data along possible tunnel routes, classifications for a wide variation in ground conditions were developed. An attempt was made to classify the various types of ground with regard to the relative ease or difficulty of tunneling operations therein. There are presented following descriptions of the various classifications of ground conditions with accompanying photographs illustrating each classification.

Intact Rock--Intact rock contains neither joints nor hairline cracks. Consequently, when breaking, it breaks across sound rock, and breakage is not influenced by joint and fracture patterns. See Figure 1.

Stratified or Schistose Rock--Stratified or schistose rock consists of individual strata with little or no resistance to parting along boundaries between strata. Strata may or may not be weakened by transverse joints. However, if transverse joints and fractures are spaced so closely as to destroy bridging action of the strata, rock is classified as very blocky and seamy, or moderately blocky and seamy. Distance between stratifications is generally less than five feet. Where distance between bedding planes is greater than five feet, the rock is better classified as moderately jointed, moderately blocky and seamy, or very blocky and seamy, depending on spacing of joints and fractures. See Figures 2 and 3.

Massive, Moderately Jointed Rock--Massive, moderately jointed rock contains joints and hairline cracks, but the blocks between the joints are

locally grown together or so intimately interlocked that vertical walls do not require lateral support. See Figure 4.

Moderately Blocky and Seamy Rock--Moderately blocky and seamy rock consists of chemically intact or almost intact rock fragments that are entirely separated from one another and imperfectly interlocked. In such rock vertical walls may require support. In moderately blocky and seamy rock, the joints and fractures are so spaced that individual blocks are larger than two feet in diameter. This classification applies to both sedimentary and crystalline rocks. See Figures 5 and 6.

Very Blocky and Seamy Rock--Very blocky and seamy rock consists of chemically intact or almost intact rock fragments which are entirely separated from each other and are imperfectly interlocked. In such rock vertical walls may require some support. Very blocky and seamy rock differs from moderately blocky and seamy rock in that the joints and fractures are so spaced that the intervening blocks are less than two feet in diameter. See Figures 7 and 8.

Completely Crushed or Unconsolidated Rock--Crushed or unconsolidated rock consists of sand to pebble sized particles that are chemically intact and are very loosely consolidated or unconsolidated. Fault gouge is sometimes present. See Figures 9 and 10.

Wet Competent Rock--Wet competent rock includes those rock types ranging from intact through very blocky and seamy under a saturated condition. Water inflows into the tunnel come from joints and fractures separating the individual blocks. Estimated inflows of 100 gpm or more from the heading must be anticipated before the ground is classified as wet competent.

Wet Crushed or Unconsolidated Rock--The term "wet" is applied to this classification when the material is saturated. Inflows into the tunnel come from interstices between the individual particles. Estimated inflows of 100 gpm or more must be anticipated before the ground is classified as wet crushed or unconsolidated.

Figure 1. Intact rock (Quartz diorite)

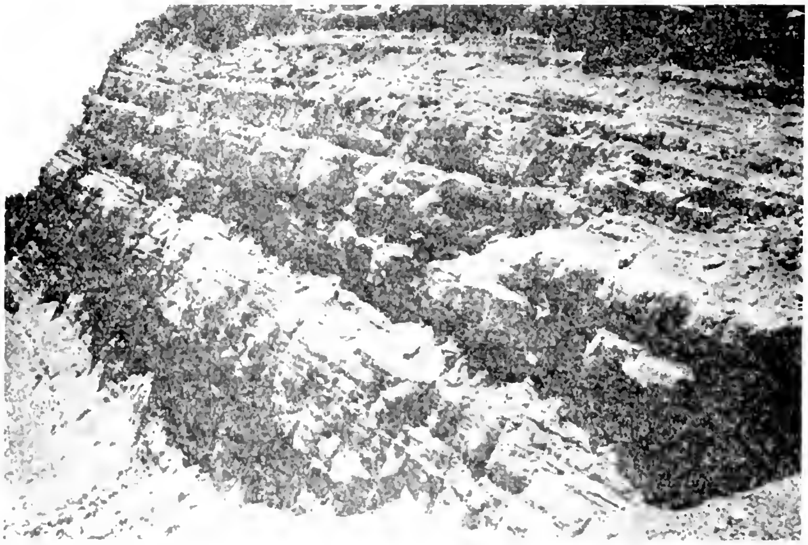

Figure 2. Stratified rock (Sandstones and shales)

Figure 3. Schistose rock (Quartz-mica-schist)

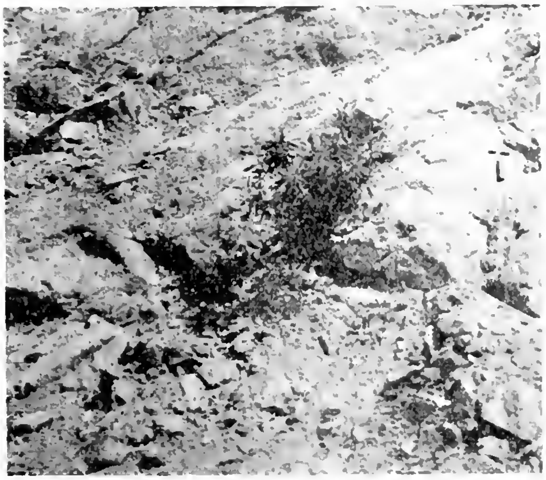

Figure 4. Massive, moderately jointed rock (Quartz diorite)

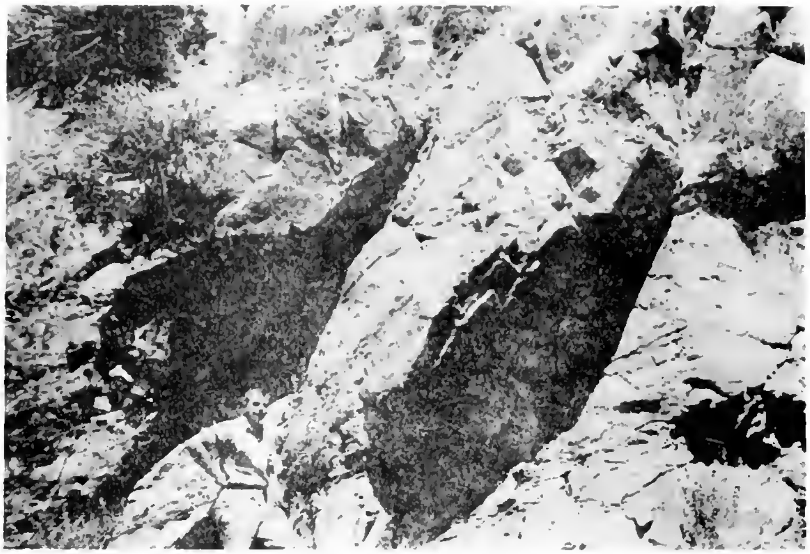

Figure 5. Moderately blocky and seamy rock (Quartz diorite)

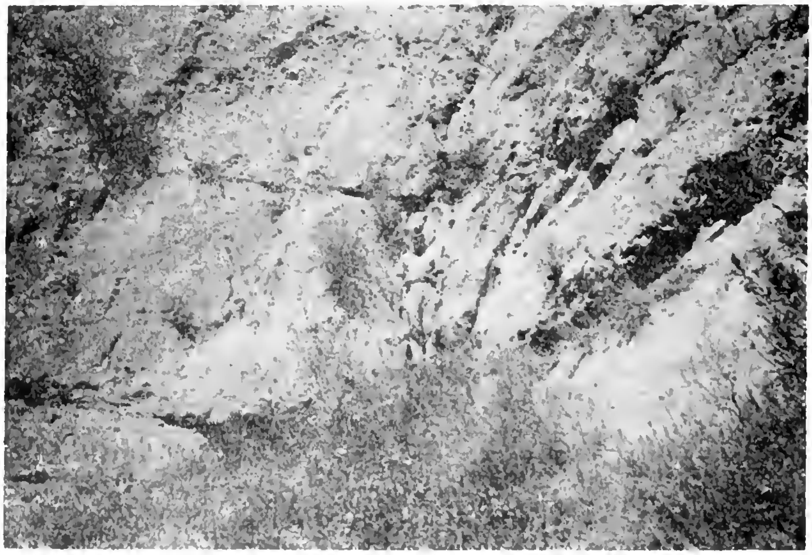

Figure 6. Moderately blocky and seamy rock (Sandstone)

Figure 7. Very blocky and seamy rock (Shale)

Figure 8. Very blocky and seamy rock (Quartz diorite)

Figure 9. Unconsolidated material (Terrace deposits)

Figure 10. Crushed material (Quartz diorite in fault zone)

Selection of Tunnel Cross Section

The dimensions and shape of a tunnel cross section are based upon the required hydraulic properties for the design discharge and upon consideration of external loading. The shape of the tunnel cross section through absolutely stable material may be selected from the economical construction standpoint. However, when the material is not absolutely stable, consideration must be given to the required resistance to external pressures No attempt is made herein to present data for detailed hydraulic or structural design of tunnel cross sections. In developing cost estimating data presented hereinafter, these design factors were considered only to the degree of detail necessary to obtain preliminary estimates of construction costs.

Typical tunnel cross sections hereinafter utilized in preparing cost estimating data are illustrated on Plate 1, "Typical Horseshoe Tunnel Section with Horseshoe Steel Support"; Plate 2, "Typical Circular Tunnel Section with Horseshoe Steel Support"; Plate 3, "Typical Circular Tunnel Section with Circular Steel Support"; Plate 4, "Typical Horseshoe Tunnel Section without Steel Support"; and Plate 5, "Typical Circular Tunnel Section without Steel Support". The hydraulic properties of the typical sections are also shown on Plates 1 through 5

From structural standpoints, the selection of tunnel cross sections for cost estimating purposes, as employed herein reflects the relative severity of ground conditions and the tunneling method which would probably be utilized for those ground conditions. In general, a horseshoe section, as illustrated on Plate 1, would be employed for relatively stable ground conditions In such ground conditions, if support is necessary, a continuous rib support would generally be employed for full face operation and rib, wall

plate, and post support would be installed with the top heading or top heading and bench method of excavation. For heavy ground conditions, a circular section, as illustrated on Plate 2, would be adopted. A circular rib would be employed where extremely severe "squeezing ground" necessitates maximum support and unusual tunneling procedures.

For purposes of cost estimating under most conditions, a concrete lining thickness of one inch per foot of lined tunnel diameter was assumed for sections utilizing steel support. It is recognized that in actual practice it might be necessary to vary lining thickness to cope with more severe ground conditions than anticipated. For severe "squeezing ground", a lining thickness of 1-1/2 inches per foot of lined tunnel diameter was assumed in sections with circular steel ribs. Where ground conditions would be stable enough so that no steel ribs are required for support, a lining thickness of three-quarters of an inch per foot of lined diameter was assumed. As indicated on Plates 1, 2, 3, 4, and 5, this thickness (t) is measured from the inside lining surface to the B line. Estimates of concrete quantities are based upon the thickness of concrete measured from the inside lining surface to the pay line. The allowance of space for blocking between the B line and the pay line varies from six to eight inches depending upon the tunnel diameter. In unsupported sections a minimum allowance of four to six inches was included.

Basic Excavation Costs

The factors which affect basic excavation costs include rate of heading advance, labor costs, equipment and material costs, dump operations, and dewatering costs. These factors and the methods used for their evaluation are discussed in the following sections.

Rate of Heading Advance

Rate of heading advance is one of the basic factors influencing cost of excavation, since labor costs are directly related thereto. In studying the construction case histories of tunnels, it was concluded that the principal items influencing rate of heading advance are physical conditions of the rock being excavated and amount of water inflow into the heading.

Presented in Table 1 are tunnel bore size, rates of advance, and rock type for the 99 tunneling projects so utilized. It should be noted that, for some of the tunneling projects listed in Table 1, only records from portions of such projects are presented. It was only in the cited portions that rates of advance could be identified with one of the standard rock conditions classified previously in this report.

A great deal of published data on tunnels, appearing in technical journals and reference books, are in print because of the interest created by exceptionally rapid rates of advance or unusually adverse conditions. It would therefore give erroneous results to incorporate these data directly into rate of heading advance curves. Because much of the data contained in Table 1 are of this nature, it was necessary to adjust the rate of heading advance curves developed therefrom to reflect a reasonable average condition for each given bore size in a given rock condition. The curves were adjusted after consultation with persons experienced in the field including the Department of Water Resources consulting engineer. Because of these adjustments, data presented in Table 1 do not in all cases plot on rate of heading advance curves presented in this report.

The curves so developed, showing rates of heading advance, are presented in Plate 6, entitled "Estimated Rates of Tunnel Heading Advance".

It will be noted on Plate 6 that curves are shown for dry headings in varying rock conditions and for wet headings in crushed or unconsolidated material and in competent rock.

It was assumed that a full face operation would be used under most rock conditions; however, in wet unconsolidated or crushed material, a multiple drift method of excavation was assumed. In dry unconsolidated or crushed material, it was assumed that the forepoling method of excavation would be used in tunnels less than 16 feet in diameter; whereas the top heading and bench method of excavation would be used in the larger bore sizes with these ground conditions.

Labor Costs

Using data from completed tunnels, advice supplied by people and organizations with tunnel construction experience, and requirements set forth by the Tunnel Master Agreement of Southern California District Council of Laborers, the probable magnitude and composition of labor crews needed for the excavation of tunnels of varying size were determined. On the basis of these estimated labor crew requirements and the rates of advance shown on Plate 6, the man-hours which would be expended per lineal foot of tunnel for each rock condition and bore size were computed. Labor costs per lineal foot of tunnel were then calculated, using union wage scales prevailing in the Southern California District Council of Laborers in January, 1957. Labor costs were computed on a basis of a six-day work week and a three shift 24-hour day, following the practice used by most contractors. There are presented in Table 2 hourly wage rates for tunnel construction personnel and the estimated composition of construction crews for various bore sizes and ground

conditions. Values presented on Table 2 were used as a basis for computation of labor costs summarized in Table 6.

The wage rates presented in Table 2 reflect basic rates paid for work in areas within reasonable distance of population centers. Based upon information supplied by the Los Angeles Building and Construction Trades Council, it was found that additional payment for subsistence must be paid to construction personnel on projects located in more remote areas. Portions of the southern California area where such subsistence payments must be paid are delineated on Plate 7, entitled "Southern California Areas Where Subsistence Payments for Construction Personnel Are Required". The Los Angeles Building and Construction Trades Council advises that payment of this subsistence amount can be by either of the following: (1) the contractor can pay the men $5.00 per diem for subsistence; or (2) the contractor can provide food and quarters for the men. In this latter case, it is customary practice for the contractor to pay $1.00 per day bonus in addition to providing food and quarters. For purposes of this report, a subsistence payment of $5.00 per day was assumed. Cost factors reflecting increased labor costs in subsistence areas are presented in Table 3 and would be added to tunnel costs for any project which falls within areas so designated. Subsistence areas in southern California are delineated on Plate 7 of this report.

Underground Equipment

Estimates were made of underground equipment required for the different tunnel bore sizes based on information obtained from records of previous tunnel construction projects and from equipment manufacturers. Equipment prices prevailing in January, 1957, supplied by the manufacturers, were used for equipment costs. Underground equipment considered in this

report includes drill jumbos, drills, mucking machines, muck cars, man cars, powder cars, locomotives, compressors, ventilator fans, and small miscellaneous equipment. A standby mucking machine and spare drills were included in the equipment requirements so that excavation operations would not be stopped by mechanical breakdown. There are presented in Table 4 a list of the various equipment items considered and the costs estimated therefor. Monthly equipment costs, based on write-off at the rate of 15 per cent per month to cover depreciation and maintenance, were reduced to a cost per lineal foot for the different bore sizes and rock conditions. These unit costs are also summarized in Table 6.

Power requirements and the cost thereof for operating underground equipment were estimated from the amount of horsepower required, the number of hours the equipment would operate during a 24-hour period, and then applying a unit cost of one cent per horsepower hour. Horsepower determination was made on ventilating and mucking equipment, compressors, and miscellaneous surface equipment which operates in conjunction with the underground equipment. These power costs are shown in Table 6.

Materials

Tunnel construction requires use of various items of expendable materials including water and ventilation pipe, small electrical equipment and cable, trackage, explosives and drill bits and rods. Estimated quantities of expendable materials required for each rock condition and bore size were computed, using information from previous tunnels and from material manufacturers. Table 5 contains a list of the various items of materials considered and the unit prices therefor. Cost per lineal foot of tunnel for these items were computed and incorporated into basic excavation costs summarized in Table 6.

Dump Operation

The cost of the dump operation is reflected in the labor excavation costs previously discussed. It was assumed that there would be a 50 per cent swell in the tunnel muck and that there would be space available in the immediate vicinity of the portal for a dump. If a disposal area is not available near the portal for a particular tunnel job, the necessary additional haulage costs based upon standard overhaul rates should be added to the costs of excavation.

Dewatering Costs

For the purposes of this report, wet headings are defined as those in which water inflows would be in excess of 100 gallons per minute. It was assumed that flows less than 100 gallons per minute would not materially impede tunnel progress and that such flows could readily be drained from the tunnel. In dewatering wet tunnel headings, it is generally found that by use of an exploratory pilot hole ahead of the face, water inflows in hard competent rocks can be grouted off before they get out of control. However, in soft sedimentary rocks and crushed zones that cannot be grouted satisfactorily, pumps and discharge lines must be installed in the tunnel headings to dispose of excess water.

For wet heading conditions in competent rock, drill hole footage, grout quantities, and costs thereof were determined for stage grouting. These costs were reduced to costs per lineal foot and were incorporated into basic excavation costs summarized in Table 6 and shown on Plate 9.

In wet, crushed or soft zones, costs of pumps and pipes needed to handle flows were determined for the following rates of flow.

Low water inflow	100- 500 gpm
Moderate water inflow	500- 1,500 gpm
Heavy water inflow	1,500-20,000 gpm

The costs of dewatering wet, crushed, or soft headings were based upon the cost of pipe required from heading to portal together with the cost of the required pumping unit. Estimating data for pipes and pumps required to handle the various flows are shown on Plate 9 and should be added to the basic tunnel excavation cost curve for wet unconsolidated or crushed rock. The cost of electrical energy for the dewatering pumps is negligible for the low and medium ranges, but for high inflows this cost would be computed on a basis of one cent per horsepower per hour.

It is worth noting that during construction of the San Jacinto Tunnel on the Colorado River Aqueduct the maximum inflow from one point was 16,000 gallons per minute, and the peak flow from all headings was approximately 40,000 gallons per minute.

Basic Excavation Cost Curves

The excavation costs for both dry and wet headings discussed in the foregoing sections were combined and are summarized in Table 6. The costs shown in these tables were plotted to obtain the basic excavation cost curves shown on Plate 8, entitled "Estimated Basic Tunnel Excavation Costs for Dry Headings", and on Plate 9, entitled "Estimated Basic Tunnel Excavation Costs for Wet Headings". These curves relate bore size to cost per lineal foot for each of the different rock conditions. As described previously and indicated on Plate 9, a special computation and addition must be made for wet headings in crushed material to take account of dewatering costs. It will be noted

in Table 6 that 25 per cent for the contractor's engineering, overhead and contingencies, and 15 per cent for contractor's profit were added into the basic excavation costs.

Steel Support Costs

For the purposes of this investigation and report, steel support requirements for tunneling were based upon methods described by Proctor and White in a publication of the Commercial Shearing and Stamping Company of Youngstown, Ohio, entitled "Rock Tunneling with Steel Support".

As the first step in developing cost estimating data for steel supports, estimates were made of unit rock loads, expressed in feet of rock on support roof, utilizing criteria presented in the afore-mentioned publication. This method establishes a relationship between the various rock conditions and the rock load expressed as a function of the tunnel bore size. The criteria are presented in a tabulation from the foregoing publication, which is reproduced as Table 7 of this report with the permission of the publishing company.

The second step involves the conversion of this unit rock load, in feet, to the total rock load in pounds to be carried by each rib set. The factors governing the total rock load on a support rib are the unlined bore diameter, the unit rock weight, and the rib spacing. In compiling cost data for tunnel support presented in this report, a rock density of 170 pounds per cubic foot was assumed. Rib spacing requirements were developed for several general rock loads as follows: for lighter rock loads, spacings of four and six feet; for moderate to heavy rock loads, spacings of two, four, and six feet; and for extremely heavy rock loads, two-foot spacing only. For rock loads in excess of 1.10 $(B + H_t)$ where circular support is needed, an 18-inch

spacing of ribs was assumed. By use of these criteria, it is possible to fix the appropriate rib spacing after identification of the nature of the rock to be penetrated. Table 10, entitled "Rib Spacing", shows customary rib spacing used for each rock classification.

The third step consists of the determination of the sizes and weights of support members. The publication, "Rock Tunneling with Steel Support", presents a procedure for computation of the sizes of support members as follows:

1. Construct a load diagram.
2. Construct a force diagram.
3. Determine maximum thrust.
4. Determine bending moment.
5. Determine maximum total stress.
6. Compute stresses in arch rib.

The following formulae are used in stress computations:

$$h = R - R^2 - C^2$$

$$Mt = hT$$

$$Mmax = 0.86\ Mt$$

$$fr - \frac{T}{A} = \frac{Mmax}{S}$$

C = Chord length between neutral axis blocking points, in inches.

R = Radius of neutral axis of rib, in inches, from load diagram.

h = Rise of arch between blocking points, in inches.

Mt = Bending moment in inch-pounds if rib sections could be pin connected at blocking points.

Mmax = Maximum bending moment, in inch-pounds, in rib continuous for at least four blocking points.

T = Thrust, in pounds, scaled from true force polygon.

S = Section Modulus of beam under consideration.

A = Sectional Area of beam under consideration, less holes, in square inches.

fr = Stress in arch portion of rib, in pounds per square inch.

Included in the foregoing publication of the Commercial Shearing and Stamping Company are tables which present sizes and weights of continuous ribs and wall plate rib members required for varying rock loads and widths of horseshoe sections computed by the foregoing procedure. Based upon the data in these tables and interpolation and extrapolation thereof, rib sizes and weights for varying bore sizes and rock conditions were computed. Independent computations were made of rib sizes and weights for continuous circular supports.

Based upon a unit cost for steel support members of 25 cents per pound, in place, estimates of costs for steel support per foot of tunnel length, for varying bore sizes and rock load conditions, were computed. These costs for varying assumed support conditions are presented in the following plates: Plate 10, entitled "Estimated Cost of Steel Support Continuous Horseshoe Rib without Invert Strut"; Plate 11, entitled "Estimated Cost of Steel Support Continuous Horseshoe Rib with Invert Strut"; Plate 12, entitled "Estimated Cost of Steel Support Rib, Wall Plate, and Post without Invert Strut"; Plate 13, entitled "Estimated Cost of Steel Support Rib, Wall Plate, and Post with Invert Strut"; and Plate 14, entitled "Estimated Cost of Steel Support Circular Rib". Rock loads that fall in between the values shown on the curves can be interpolated to determine cost. As previously indicated, the curves are for rocks with a density of 170 pounds per cubic foot. For rocks whose density deviates considerably from the 170 pounds per cubic foot, it would be necessary to make appropriate adjustments therefor. Values on

the curves include the costs of butt plates and foot plates and miscellaneous steel. A separate curve is shown on each plate for the cost of concrete foot blocks needed for each rib set.

It was assumed that continuous rib steel support would be used in the full face and forepoling methods of excavation. This means that continuous ribs would be used as a basis for estimating steel support for all rock conditions except for (1) unlined bore sizes larger than 16 feet in diameter in dry crushed or unconsolidated material, and (2) all bore sizes in wet crushed or unconsolidated material. Under the latter two conditions, it was assumed that excavation would be conducted by top heading and bench or multiple drift methods of excavation, and, consequently, because of the nature of the excavation procedure, rib, wall plate, and post supports were used as a basis for estimating steel support. As previously indicated, under conditions of severe squeezing ground, it was assumed that continuous circular ribs would be required.

In hard and intact rock and under unusually good conditions in massive, moderately jointed or stratified or schistose rock, steel support may not be required. When these conditions are anticipated, no costs would be included for steel support.

Timber Lagging and Support Costs

Estimates of the quantities of timber required for lagging were made for varying bore sizes in different rock conditions. These estimates were based upon use of standard 3-inch by 12-inch lagging on spacing varying from "skintight" to 3-foot centers depending upon rock conditions. The quantities calculated were increased by 50 per cent to provide for miscellaneous timber for blocking and collar bracing. Timbering costs per lineal

foot of tunnel were computed using a unit cost of $350 per 1,000 board feet for timber in place. Presented on Plate 15, entitled "Estimated Cost of Timber Lagging for Tunnels", are estimated costs of timber lagging, including allowance for miscellaneous blocking and bracing.

For wet headings in unconsolidated, completely crushed, or fault zone materials, a multiple drift method of excavation would be used. This method requires the use of temporary timber support for the wall plate drifts and top drift before rib, wall plate, and post steel supports are placed. Estimated timber requirements for the two side drifts and the top drifts were calculated for varying bore sizes based upon use of 12-inch by 12-inch timbers for side drifts and 10-inch by 10-inch timbers for top drifts, all placed on 2-foot centers. Costs for timber support under such conditions are presented graphically on Plate 16, entitled "Estimated Cost of Additional Timber Support Required for Multiple Drifts". These timber support costs as indicated in the plate title are in addition to those shown on Plate 15 and are to be added thereto where wet crushed or unconsolidated material is anticipated and when multiple drift tunneling would be necessary.

No costs for timber would be computed for portions of tunnels where steel support would not be required.

Concrete Lining Costs

Estimates were prepared of quantities and costs of concrete lining and of grouting behind the lining. As described earlier in this report, required concrete quantities were related to tunnel cross sectional dimensions. Estimates were based upon a lining thickness of one inch per foot of finished diameter for ground conditions in which a horseshoe rib would be employed. Where severe ground conditions would be encountered, requiring

the use of a circular rib, a lining thickness of one and one-half inches per foot of finished diameter was assumed. Where ground conditions would be so stable that steel support would not be required, a lining thickness of three-quarters of an inch per foot of finished diameter was assumed. Concrete lining quantities were taken from the inside tunnel surface to the pay line. The amount of concrete was determined for varying tunnel diameters, and cost curves were prepared for five different cross section designs: horseshoe support with horseshoe lining, horseshoe support with circular lining, circular support with circular lining, horseshoe lining without support, and circular lining without support. A unit cost of concrete, in place, of $35.00 per cubic yard was used on the estimates.

An additional amount was added to the concrete lining cost to cover the cost of grouting behind the tunnel lining to fill the void space between the lining and the rock. Grouting costs reflect provision for drilling grout holes two and one-half feet in depth through the lining, at about 25-foot centers. These holes would be 30 degrees off the center of the arch alternately on opposite sides of the center line. It was assumed that three to five cubic feet of grout per lineal foot of tunnel would be required, varying directly with the bore size, at a unit cost of $3.50 per cubic foot.

The foregoing costs of concrete lining and grouting are presented on Plate 17, entitled "Estimated Cost of Concrete Lining for Tunnels with Horseshoe Steel Support"; Plate 18, entitled "Estimated Cost of Concrete Lining for Tunnels without Steel Support"; and Plate 19, entitled "Estimated Cost of Concrete Lining for Tunnels with Circular Support".

Appurtenant Tunnel Construction Facilities

In addition to the items of cost of tunnel construction discussed in the foregoing sections, appurtenant items of construction work and equipment are required above ground. These items vary greatly for different tunnel construction projects depending generally upon the terrain surrounding the portals, the relative remoteness of the project from sources of supplies and labor and the climatic conditions at the job site. The following tabulation lists the various items of this nature:

- Access Roads
  - Construction
  - Maintenance
- Power Supply
  - Installation of power lines
  - Construction of generating plant if power line installation not feasible
- Surface Buildings
  - Change and washroom facilities
  - Blacksmith shop
  - Machine shop
  - Compressor building
  - Powder magazine
  - Cap magazine
  - Miscellaneous buildings
- Construction Camp (if needed)
- Portal Excavation
- Water Supply
- Sewer System

The foregoing facilities must generally be evaluated individually for each project. Estimates of cost should be prepared for each of the items required in the project under consideration and added to the construction costs obtained by use of the previously described curves. No attempt is made herein to present criteria and standards for estimating costs for these appurtenant facilities as they lend themselves generally to standard cost estimating procedures or can be obtained from equipment manufacturers or suppliers.

Changes in Construction Costs

It is recognized that the unit costs employed in this report, which reflect price levels of January, 1957, are subject to substantial change with time. With changes in construction cost indices from those of January, 1957, it will be necessary to modify costs obtained from the curves developed herein by application of appropriate factors.

It is not considered feasible to adjust excavation costs by application of an over-all cost index, because this item includes costs for labor, equipment, and materials, and each of these items probably would change at a different rate. Of the over-all excavation costs summarized in Table 6, labor constitutes approximately 53 per cent of the total, equipment 28 per cent, and materials 13 per cent. It is suggested that revisions of the basic excavation cost be made by determining separate cost indices for labor, equipment, and materials, and applying them in proportion to the afore-mentioned percentages.

Costs for steel support, timber, and concrete can rapidly be revised by application of appropriate price indices for these items.

Should radical changes in tunneling techniques develop whereby rates of advance, labor crews, or equipment and material requirements are greatly changed, a complete revision of the cost and supporting curves would be required.

CHAPTER III. OUTLINE OF TUNNEL COST ESTIMATING PROCEDURE

There is presented in this chapter a step by step procedure for preparation of an estimate of cost for a tunnel construction project, utilizing the curves and data described and contained in this report. Standard form sheets for tabulation and computation of the estimating data are contained in Table 9. The procedure by steps presented by item headings shown in Table 9 is as follows:

Preparation of Field Data

Step 1

Information on rock conditions and other data needed to enter into the various cost estimating curves presented in this report are determined by geologists working in the field and are entered in the tabular form shown in Table 8. Sample notations indicated on this form are typical of the manner in which field men would fill in their notations.

A - Basic Excavation Cost

Step 2

The number of lineal feet of tunnel penetrating each rock condition is obtained from Table 8 and is entered in the first column of Table 9.

Step 3

Excavation costs for each rock condition are determined from the cost curves on Plates 8 and 9 and entered in the second column of Table 9.

Step 4

Plate 5, which delineates areas where subsistence payment is required, is then checked. If the tunnel project in question is within an area where subsistence payments are required, the additional cost for subsistence is entered in the third column. These costs are obtained from Table 3.

Step 5

The sum of the second and third columns is multiplied by the number of lineal feet in the first column, and the product entered in the fourth column.

B - Dewatering Cost

Step 6

Where it is indicated that water-bearing zones will be penetrated by the tunnel, the estimated cost for dewatering these zones is determined. When wet competent rocks are involved, it is assumed that water inflows can be curtailed sufficiently by grouting. Additional cost incurred by the grouting operation is incorporated into the cost curve shown for wet competent rock on Plate 9, entitled "Estimated Basic Tunnel Excavation Costs for Wet Headings", and consequently an additional calculation will not be required to determine the cost of dewatering under these conditions.

In wet crushed or unconsolidated conditions, it is assumed that water inflows at the heading will have to be removed. To determine the cost of dewatering under these conditions, it is first necessary to determine the maximum number of lineal feet to the portal and insert this figure in the

first column under "Dewatering Cost". If there is a question as to which portal will be used for discharge, the rate of heading advance curves on Plate 6 should be utilized to determine which heading will penetrate the wet zone first. The portal serving the first heading into the wet zone will be utilized as the discharge portal.

Step 7

The cost per foot for discharge pipe from the pumps is determined from Plate 9 and placed in the second column under "Dewatering Cost".

Step 8

Pump costs for the estimated discharge are determined from Plate 9 and entered in the third column.

Step 9

The number of lineal feet of pipe and cost per lineal foot in columns 1 and 2 are multiplied and the cost of the pump in column 3 is added. The resultant total dewatering cost is entered in the fourth column.

C - Steel Support Cost

Step 10

For determining steel support costs the number of lineal feet of tunnel under each rock load and rib spacing is obtained from Table 8 and entered in the first column under "Steel Support Cost". Customary rib spacings for various rock conditions are shown in Table 10.

Step 11

Costs of steel support are determined from the appropriate curves shown on Plates 10, 11, 12, 13, and 14, utilizing rib spacing and rock loads specified in the field geologists data presented in Table 8. The following criteria are to be used in selecting the appropriate curve:

1. For all bore sizes in intact, moderately jointed, moderately blocky and seamy, very blocky and seamy, and wet competent rock, the cost curve for the continuous rib without invert strut shown on Plate 10 will be used. This curve will also be used for unlined bore sizes less than 16 feet in diameter in dry crushed or unconsolidated material.
2. When squeezing ground is expected under the foregoing conditions in Item 1, use of an invert strut will be recommended on the tabulation of field observations shown in Table 8 and the cost of steel support is obtained from the curve for continuous ribs with invert strut shown on Plate 11.
3. For bore sizes whose unlined diameter is greater than 16 feet in dry crushed or unconsolidated materials and for all bore sizes in wet crushed or unconsolidated materials, steel support costs will be obtained from the curve for rib, wall plate, and post support without invert strut shown on Plate 12.
4. When moderate squeezing ground is anticipated for conditions of Item 3, use of an invert strut will be recommended in Table 8. Costs for steel support will then be obtained from the cost curve for rib, wall plate, and post support with an invert strut shown on Plate 13.

5. When estimated rock roads are in excess of 1.10 ($B + H_t$), it is assumed that circular ribs will be needed to withstand external pressures and steel support costs will then be obtained from cost curves shown for circular ribs shown on Plate 14.

Step 12

The cost per foot of tunnel for steel support is multiplied by the number of lineal feet shown in column 1 and the product entered in the third column.

D - Costs of Foot Blocks

Step 13

Costs for foot blocks are determined by dividing the number of feet of tunnel under each rock loading by the assumed rib spacing, thus obtaining the number of rib sets. The number of sets are then placed in the first column. Cost per rib set for foot blocks is then determined from the curves on Plates 10, 11, 12, and 13, and posted in the second column. Total cost for foot blocks is determined by multiplying the number of sets by the cost per set for foot blocks. This value is entered in the third column under D - "Cost of Foot Blocks".

E - Timber Lagging and Support Cost

Step 14

In order to determine timbering costs, the number of lineal feet of each rock condition is entered in the first column under "Timber Lagging

and Support Cost". No costs will be determined for timber in sections of tunnel that do not require steel support.

Step 15

Appropriate costs for lagging are determined from Plate 15 and placed in the second column opposite "Lagging".

Step 16

The number of lineal feet is multiplied by the cost per foot and the product entered in the third column.

Step 17

In wet crushed or unconsolidated materials, temporary timber support is required for wall plate and top drifts. Where this type of material is encountered, enter the number of lineal feet thereof penetrated by the tunnel in the first column opposite "Timber Support".

Step 18

Determine the appropriate cost for timber support from the cost curve on Plate 16 and insert this cost in the second column.

Step 19

Multiply the number of lineal feet by the cost per foot for timber support and enter the product in the third column.

F - Concrete Lining Cost

Step 20

Costs for concrete lining are determined by obtaining the cost per foot for the appropriate tunnel section from the cost curves presented on Plates 17, 18, and 19, and multiplying the cost per foot by the number of feet of section that will be used in the proposed tunnel. The result is posted in the third column opposite "Concrete Lining".

G - Appurtenant Tunnel Construction Facilities

Owing to the variation in the problems of access, availability of power and water, and the adaptability of the local terrain for a construction camp, items in this category must be computed for each individual tunnel site. Costs determined for these items are listed in the appropriate boxes under fixed expenditures.

Final Cost Estimate

The estimating form presented in Table 9 is organized in such a manner that the individual components of the tunnel cost estimate appear in the extreme right hand columns. By adding all of the subtotals of items in these columns, the estimated tunnel construction cost is obtained. It will be noted that, with the exception of basic excavation costs, the cost estimating data presented in this report are based upon unit prices obtained from analysis of contract bidding on construction projects. Therefore, contractor's profit and contingency allowances would be included in these latter items. With respect to basic excavation costs, items of 15 per cent for contractor's profit and 25 per cent for contractor's overhead and contingencies have been included.

In general, tunneling projects constitute only a portion of a larger aqueduct project; and, therefore, it is assumed that the administrative agency in preparing a preliminary estimate would include an additional allowance for engineering and contingencies in summarizing over-all project costs including tunneling costs. Therefore, the tunnel cost estimating form in Table 9 includes no items for engineering and contingencies but such allowance should be added to costs obtained by the cost estimating procedure hereinbefore described.

TABLES

TABLE 1

RATES OF ADVANCE FOR VARYING ROCK CONDITIONS AND BORE SIZES ON COMPLETED TUNNEL CONSTRUCTION PROJECTS

Tunnel project	Unlined bore size	Rate of advance per 8-hour shift*	Rock condition
Allt-Na-Lairige (Scotland)	6 x 8	12	Massive, moderately jointed.
Alva B. Adams (Colorado)	12	13	Massive, moderately jointed.
		15	Moderately blocky and seamy.
Baltimore and Ohio (Clarksburg, West Virginia)	28 x 31	6.5	Hard stratified.
Baltimore Water Tunnel	10	15	Hard and intact rock.
Big Creek #4 (California)	24	12	Moderately blocky and seamy.
Bingham Tunnel	10	16	Very blocky.
	10	5	Very blocky and seamy, wet.
Blue Ridge	20 x 26	9	Moderately blocky and seamy.
Boqueron (Venezuela)	14	11	Very blocky and seamy.
British Columbia Nickel Mine	10 x 8	6	Massive, moderately jointed.
Butt Lake	15	12	Moderately blocky and seamy.
Broadway (San Francisco)	28 x 22	5	Stratified and completely crushed.
Caribou #2	15	14	Very blocky and seamy, wet.
		6	Unconsolidated.
Carlton (Colorado)	11	18	Moderately blocky and seamy.

RATES OF ADVANCE FOR VARYING ROCK CONDITIONS AND BORE SIZES
ON COMPLETED TUNNEL CONSTRUCTION PROJECTS
(continued)

Tunnel project	Unlined bore size	Rate of advance per 8-hour shift*	Rock condition
Chicago Sewer	24	12	Stratified.
Cincinnati Sewer	11	8	Unconsolidated.
Colorado River Aqueduct			
Colorado River	19	11	Moderately blocky and seamy.
Copper Basin	19	9	Very blocky and seamy.
Whipple Mountain	19	12	Schistose.
Iron Mountain (East)	19	8	Schistose, wet.
Iron Mountain (West)	19	9	Completely crushed.
Coxcomb	19	10	Massive, moderately jointed.
East Eagle	19	9	Moderately blocky and seamy.
West Eagle (East)	19	8.5	Moderately blocky and seamy.
West Eagle (West)	19	8	Moderately blocky and seamy.
Hayfield #1	19	10	Moderately blocky and seamy.
Hayfield #2	19	12	Moderately blocky and seamy.
Cottonwood	19	10	Very blocky and seamy.
Mecca Pass #1, 2, and 3	19	8.5	Very blocky and seamy.
East Coachella	19	9	Very blocky and seamy.
Thousand Palms #1	19	8.5	Very blocky and seamy.
Thousand Palms #2	19	7.5	Very blocky and seamy.
Wide Canyon #1	19	8	Very blocky and seamy.
Wide Canyon #2	19	6	Very blocky and seamy.
Seven Palms	19	7.5	Very blocky and seamy.
Long Canyon	19	10	Very blocky and seamy.
Blind Canyon	19	11	Very blocky and seamy.
Morongo #1	19	11.5	Very blocky and seamy.
Morongo #2	19	17	Very blocky and seamy.
Whitewater #1	19	11	Completely crushed.
Whitewater #2	19	14	Completely crushed.
Bernasconi	19	8	Moderately blocky and seamy.
Val Verde	19	3	Very blocky and seamy, wet.
San Jacinto	[illegible]	2	Moderately blocky and seamy, wet.
		10	Moderately blocky and seamy.

RATES OF ADVANCE FOR VARYING ROCK CONDITIONS AND BORE SIZES ON COMPLETED TUNNEL CONSTRUCTION PROJECTS (continued)

Tunnel project	Unlined bore size	Rate of advance per 8-hour shift*	Rock condition
Prospect Mountain (Colorado)	12	12 10	Schistose. Very blocky and seamy.
Delaware Aqueduct Tunnel	13	10	Completely crushed.
Downsville Dam Diversion (New York)	40	5	Hard stratified.
Dry Canyon (California)	12	15	Hard stratified.
East Delaware	15	15	Hard stratified.
Ecumbene-Tumut (Australia)	24	14	Hard stratified.
Eklutna, Chugach Mountain (Alaska)	12	18 11 4	Hard stratified. Moderately blocky. Shear zones.
Feather River	25	7	Moderately blocky and seamy.
Fort Peck Dam Diversion (Montana)	15	14	Stratified.
Fort Spring C & O RR (West Virginia)	20 x 22	0.2 3	Completely crushed, wet. Completely crushed, dry.
Gateway (Wasatch Mountain, Utah)	11	19 17	Schistose. Moderately blocky and seamy.
Gaviota (California)	25	10	Hard stratified.
Glendo (Wyoming)	21	13	Hard stratified.
Grootvlei Houlage Way (South Africa)	13	15	Hard stratified.
Guayo Prieto Yauco (Puerto Rico)	11	8	Moderately blocky and seamy.

RATES OF ADVANCE FOR VARYING ROCK CONDITIONS AND BORE SIZES
ON COMPLETED TUNNEL CONSTRUCTION PROJECTS
(continued)

Tunnel project	Unlined bore size	Rate of advance per 8-hour shift*	Rock condition
Halkyn (Wales)	10	3.5	Moderately blocky and seamy, wet.
Hultman (Massachusetts)	12	11	Hard stratified.
Hungry Horse (Canada)	36	7	Very blocky and seamy.
Hyperion Sewer Tunnel (California)	12	12	Completely crushed.
Isers-Arc (Doren River, France)	23	10 8	Hard stratified. Moderately blocky and seamy.
Kitimat (British Columbia)	25	13	Moderately blocky and seamy.
La Cienega Relief Sewer (California)	8.5	10 8	Hard stratified. Completely crushed.
Leadville (Colorado)	9 x 11	1 10	Completely crushed, wet. Completely crushed, dry.
Loch Fannich (Scotland)	12	7	Schistose.
Loch Luichart (Scotland)	17	8	Schistose.
Machkund (South India)	19	7	Moderately blocky and seamy.
Meig (Scotland)	12	15	Schistose.
Neversink Delaware Aqueduct (New York)	12	13	Hard stratified.
New Elkhorn	36 x 35	6	Very blocky and hard stratified.
New York Sewer	10	15	Schistose.

RATES OF ADVANCE FOR VARYING ROCK CONDITIONS AND BORE SIZES
ON COMPLETED TUNNEL CONSTRUCTION PROJECTS
(continued)

Tunnel project	Unlined bore size	Rate of advance per 8-hour shift*	Rock condition
Niagara Falls Hydroelectric (Canada)	51	5	Moderately blocky and seamy.
Norfolk & Western Railroad (West Virginia)	36 x 35	7	Hard stratified.
North Poudre (Colorado)	11	17	Hard stratified.
Oswego Tunnel	10	11	Stratified.
Owens Gorge #1 and #2	13.5	18	Very blocky and seamy.
		12	Moderately blocky and seamy.
Pit#4	26	13	Very blocky and seamy.
Quabbin (Boston, Massachusetts)	14	10	Moderately blocky and seamy.
Rams Horn (Colorado)	11.5	16	Moderately blocky and seamy.
Rimutaka (New Zealand)	17 x 15	13	Massive, moderately jointed.
Rock Creek	25	10	Moderately blocky and seamy.
Roundout (New York)	17	6	Moderately blocky and seamy, wet.
	17	10	Hard stratified.
	20	0.8	Shear zones, wet.
Sainani (Bolivia)	7	5	Moderately blocky and seamy.
San Diego Aqueduct Tunnels 7 (California)	9	9	Moderately blocky and seamy.
Squamish-Garibaldi (Canada)	18	16	Moderately blocky and seamy.

RATES OF ADVANCE FOR VARYING ROCK CONDITIONS AND BORE SIZES ON COMPLETED TUNNEL CONSTRUCTION PROJECTS (continued)

Tunnel project	Unlined bore size	Rate of advance per 8-hour shift*	Rock condition
Squirrel Hill (Pennsylvania)	36 x 26	7.5 0.4	Hard stratified. Shear zones.
Stanislaus (California)	9 x 10	10	Massive, moderately jointed.
Tahtsa Kitimat Power Site (Canada)	29	11	Moderately blocky and seamy.
Tecolote (California)	9	10 2.5	Stratified. Completely crushed, wet.
Tennessee Creek (North Carolina)	15	14	Hard schistose.
T. J. Evans (Pennsylvania Turnpike)	33 x 27	8	Hard stratified.
Tingambato	15	12	Massive, moderately jointed.
Treasury (Colorado)	9	13	Moderately blocky and seamy.
West Branch Reservoir (New York)	19.5	12	Schistose.
West Rock (Connecticut)	12	12	Very blocky and seamy.
White Point (California)	17	12	Stratified.
Woodhead (England)	32	8	Very blocky and seamy.

*Note Rate of advance is average for specific rock condition and does not represent over-all average advance for tunnel.

TABLE 2

HOURLY WAGE RATES AND ESTIMATED PERSONNEL REQUIREMENTS OF TUNNEL CONSTRUCTION CREWS IN SOUTHERN CALIFORNIA

(Prevailing wages of January 1, 1957)

Item	Hourly wage rate	Number of personnel per shift: 9 - 14 ft. unlined diameter: No. of men	No. of shifts	15 - 24 ft. unlined diameter: No. of men	No. of shifts
Shifter	$ 3.22	1	3	1	3
Miner	2.92	See page		See page	
Chucktender	2.77	following		following	
Nipper	2.77	1	3	2	3
Mucking machine operator	3.44	1	3	1	3
Oiler	2.77	1	3	1	3
Motorman	2.97	3	3	4	3
Brakeman	2.77	3	3	4	3
Dumpman	2.67	1	3	2	3
Electrical foreman	4.31	1	3	1	3
Electrician	3.60	2	3	2	3
Compressor man	2.70	1	3	1	3
Warehouse man	2.35	1	3	1	3
Warehouse man helper	2.00	1	3	1	3
Carpenter	3.13	1	1	2	1
Master Mechanic	4.10	1	3	1	3
Heavy duty mechanic	3.05	2	3	2	3
Blacksmith	3.35	1	1	1	1
Blacksmith helper	3.00	1	1	1	1
Drill doctor	3.50	1	1	1	1
Powder man	2.92	1	3	1	3
Pipe foreman	3.90			1	1
Pipe fitter	3.65			2	1
Track boss	2.92	1	3	1	3
Track crew	2.66	3	3	4	3
Labor crew	2.66	1	3	2	3
Truck driver	2.47	1	3	1	3
First aid man	22.00/day-one man on 24 hours off 24 hours				
Walker	3.75	1	3	1	3
Timekeeper	2.30	1	3	1	3
Office men	2.35	3	1	3	1
Bookkeeper	2.45	2	1	2	1
Superintendent	5.89	1	1	1	1

HOURLY WAGE RATES AND ESTIMATED PERSONNEL
REQUIREMENTS OF TUNNEL CONSTRUCTION CREWS
IN SOUTHERN CALIFORNIA
(continued)

Item	Number of personnel per shift for unlined tunnel diameter							
	9'-10'	11'-12'	13'-14'	15'-16'	17'-18'	19'-20'	21'-22'	23'-24'
Miner	4	5	6	7	8	9	10	12
Chucktender	4	5	6	7	8	9	10	12

These personnel work a three shift day.

TABLE 3

ESTIMATED COSTS INCURRED FOR SUBSISTENCE PAYMENTS TO TUNNEL CONSTRUCTION PERSONNEL IN SOUTHERN CALIFORNIA

(Prevailing costs of January 1, 1957)

Unlined tunnel diameter	Cost in dollars per lineal foot of tunnel for given rock conditions						
	Stratified or schistose	Intact or moderately jointed	Moderately blocky and seamy	Very blocky and seamy	Crushed or unconsolidated	Wet competent	Wet crushed or unconsolidated
28	45	56	51	59	223	186	558
27	43	53	48	56	186	159	558
26	38	49	43	49	147	147	515
25	37	47	41	47	129	129	344
24	32	37	34	37	96	120	320
23	31	36	33	36	87	107	320
22	28	33	30	32	75	100	225
21	27	32	29	31	69	90	225
20	26	30	27	29	62	87	174
19	25	29	26	28	58	79	174
18	23	27	25	26	53	76	140
17	23	26	24	25	49	70	140
16	21	25	23	24	45	68	135
15	21	25	22	23	43	62	116
14	17	20	18	18	33	48	95
13	16	19	17	18	32	44	83
12	15	18	16	17	28	42	79
11	15	17	15	16	26	42	79
10	15	17	15	16	26	43	87
9	15	18	16	16	29	43	101

TABLE 4

COSTS OF ITEMS OF UNDERGROUND
TUNNEL CONSTRUCTION EQUIPMENT
IN SOUTHERN CALIFORNIA

(Price levels of January, 1957)

Item	Cost
Conway 100-1 loader (bore sizes 18' or over)	$47,800 each
Conway 100 loader (bore sizes 13' - 17')	36,600 each
Eimco 40-H loader (bore sizes 12' and under)	14,700 each
Gantry type drill jumbo with piping, tugger hoists, cherry picker and miscellaneous equipment (bore sizes 13' and above)	8,700 each to 14,300 each
Mainline type drill jumbo with piping (12' and under) and miscellaneous equipment	6,000 each
Following items vary in number required and size with tunnel diameter:	
Rock drills	1,150 each
Hydraulic jibs	1,650 each
15-ton locomotives with battery boxes	13,600 each
8 -ton locomotives with battery boxes and batteries	22,470 each
56-cell, 31-plate Exide batteries	13,633 each
1,200 cfm air compressors	18,795 each
8-cubic yard side dump muck cars	2,525 each
5-cubic yard side dump muck cars	1,750 each
Man cars	2,800 each
Flat cars	2,200 each
Powder cars	3,300 each
Circuit chargers	3,460 each
In-line ventilation fans 15 hp	1,500 each
Water pumps 100 - 20,00 gpm capacity	800 each to 5,000 each

TABLE 5

UNIT COSTS OF EXPENDABLE ITEMS OF MATERIAL FOR TUNNEL CONSTRUCTION IN SOUTHERN CALIFORNIA

(Price levels of January, 1957)

Item	Cost
Pipe	
Water 2"	$ .45/ft.
Air 6"	1.40/ft.
Ventilation 30"	7.35/ft.
Electrical	
Mine Power cable	3.60/ft.
Lighting cable	1.96/ft.
3 KVA transformers	90.00 each
4160v 5KVA outdoor oil circuit breakers	1,925.00 each
225KVA 3-phase 4160v transformer	4,500.00 each
Motor control 4160v	5,500.00 each
Trackage	
60-lb. rail	78.00/ton
Ties	1.46 each
Spikes	13.50/100 lbs.
Tie plates	88.00/ton
Explosives	
1-1/4 x 8 - 40% semi-gel	18.45/100 lbs.
No vent tunnel delays	
12' regular cap	19.75/100
12' standard #1 delay	27.25/100
12' standard #2 delay	27.75/100
12' standard #3 delay	28.00/100
12' standard #4 delay	28.25/100
Drills	
Carbide inset bits	14.20 each
Drill rods	15.00 each

TABLE 6

SUMMARY OF ESTIMATED BASIC COSTS OF TUNNEL EXCAVATION

(Price levels of January 1, 1957)

Unlined tunnel diameter in feet	Rate of heading advance in feet per 24-hour day	Labor dollars per foot	Underground equipment dollars per foot	Power dollars per foot	Expendable materials: Pipe track etc. dollars per foot	Expendable materials: Explosives dollars per foot	Expendable materials: Drill bits and rods dollars per foot	Subtotal dollars per foot	15% profit 25% contingencies dollars per foot	Miscellaneous items* dollars per foot	Total cost of excavation dollars per foot
Dry Headings in Stratified or Schistose Rock											
24	30	162	86	6.62	20.70	24.56	3.30	304	122	38.08	464
23	31	156	83	6.40	20.70	22.94	3.12	292	117	34.98	444
22	32	142	80	6.19	20.70	21.61	3.00	274	110	32.00	416
21	33	138	77	6.00	20.70	20.06	2.82	265	106	29.16	400
20	34	130	75	5.82	20.70	18.80	2.70	254	102	26.44	382
19	35	126	73	5.65	20.70	17.31	2.52	246	98	28.86	368
18	36	118	70	5.48	20.70	16.31	2.40	232	93	21.42	346
17	37	115	55	4.67	20.70	14.95	2.22	213	85	19.10	317
16	38	108	54	4.42	20.70	13.61	2.10	203	81	16.92	301
15	39	105	52	4.31	20.70	12.28	1.92	196	78	14.88	289
14	40	85	50	4.20	20.70	11.96	1.80	174	70	12.96	257
13	41	83	49	4.09	20.70	10.60	1.62	167	68	11.18	248
12	42	78	26	4.00	20.70	9.54	1.50	140	56	9.52	206
11	42	78	26	4.00	20.70	8.26	1.32	138	55	8.00	201
10	41	76	26	4.00	20.70	7.30	1.20	136	54	6.62	197
9	40	76	26	4.00	20.70	6.12	1.02	136	54	5.36	197

SUMMARY OF ESTIMATED BASIC COSTS OF TUNNEL EXCAVATION
(continued)

Unlined tunnel diameter in feet	Rate of heading advance in feet per 24-hour day	Labor dollars per foot	Underground equipment dollars per foot	Power dollars per foot	Expendable materials: Pipe track etc. dollars per foot	Expendable materials: Explosives dollars per foot	Expendable materials: Drill bits and rods dollars per foot	Subtotal dollars per foot	15% profit 25% contingencies dollars per foot	Miscellaneous items* dollars per foot	Total cost of excavation dollars per foot
Dry Headings in Massive Moderately Jointed or Intact Rock											
24	26	186	99	8.34	21	33.35	3.30	350	140	38.08	528
23	27	180	96	8.34	21	31.01	3.12	339	136	34.98	510
22	27	169	95	8.00	21	28.99	3.00	325	130	32.00	487
21	28	163	91	7.68	21	26.79	2.82	313	125	29.16	467
20	29	152	88	7.38	21	24.89	2.70	296	118	26.44	440
19	30	147	85	7.38	21	22.82	2.52	286	114	23.86	424
18	31	137	82	7.11	21	21.07	2.40	270	108	21.42	399
17	32	133	64	6.00	21	19.54	2.22	246	98	19.10	363
16	33	125	62	5.79	21	17.51	2.10	236	94	16.92	347
15	33	125	62	5.60	21	15.71	1.92	232	93	14.88	340
14	34	100	59	5.25	21	15.41	1.80	202	81	12.96	296
13	35	97	58	4.94	21	13.69	1.62	197	79	11.18	287
12	36	90	31	4.67	21	12.17	1.50	159	64	9.52	233
11	37	88	30	4.54	21	10.48	1.32	155	62	8.00	225
10	36	86	30	4.54	21	9.13	1.20	152	61	6.62	220
9	34	86	30	4.54	21	7.60	1.02	152	61	5.36	220

SUMMARY OF ESTIMATED BASIC COSTS OF TUNNEL EXCAVATION
(continued)

Unlined tunnel diameter in feet	Rate of heading advance in feet per 24-hour day	Labor dollars per foot	Underground equipment dollars per foot	Power dollars per foot	Expendable Materials: Pipe track etc. dollars per foot	Expendable Materials: Explosives dollars per foot	Expendable Materials: Drill bits and rods dollars per foot	Subtotal dollars per foot	15% profit 25% contingencies dollars per foot	Miscellaneous items* dollars per foot	Total cost of excavation dollars per foot
Dry Headings in Moderately Blocky and Seamy Rock											
24	28	173	92	7.38	21	26.33	3.30	322	129	38.08	489
23	29	167	89	7.11	21	24.56	3.12	312	125	34.98	472
22	30	152	85	6.85	21	23.08	3.00	291	116	32.00	439
21	31	147	82	6.62	21	21.41	2.82	281	112	29.16	422
20	32	138	79	6.40	21	20.02	2.70	267	107	26.44	400
19	33	139	77	6.19	21	18.41	2.52	259	104	23.86	387
18	34	125	74	6.00	21	17.12	2.40	245	98	21.42	364
17	35	122	56	5.09	21	15.87	2.22	224	90	19.10	333
16	36	114	56	4.80	21	14.39	2.10	212	85	16.92	314
15	37	111	56	4.67	21	12.96	1.92	207	83	14.88	305
14	38	90	53	4.52	21	12.67	1.80	184	74	12.96	271
13	39	87	52	4.31	21	11.22	1.62	177	71	11.18	259
12	40	81	28	4.20	21	10.06	1.50	145	58	9.52	213
11	41	79	27	4.09	21	8.71	1.32	141	56	8.00	205
10	40	78	27	4.09	21	7.67	1.20	139	56	6.62	202
9	39	78	27	4.09	21	6.92	1.02	139	56	5.26	202

SUMMARY OF ESTIMATED BASIC COSTS OF TUNNEL EXCAVATION
(continued)

Unlined tunnel diameter in feet	Rate of heading advance in feet per 24-hour day	Labor dollars per foot	Underground equipment dollars per foot	Power dollars per foot	Expendable Materials: Pipe track etc. dollars per foot	Expendable Materials: Explosives dollars per foot	Expendable Materials: Drill bits and rods dollars per foot	Subtotal dollars per foot	15% profit 25% contingencies dollars per foot	Miscellaneous items* dollars per foot	Total cost of excavation dollars per foot
Dry Headings in Very Blocky and Seamy Rock											
24	26	186	99	8.34	21	21.06	3.30	338	138	38.08	511
23	27	180	96	8.00	21	19.71	3.12	328	131	34.98	494
22	28	163	91	7.68	21	18.65	3.00	305	122	32.00	459
21	29	157	88	7.38	21	17.37	2.82	293	117	29.16	439
20	30	147	85	7.11	21	16.36	2.70	279	112	26.44	417
19	31	142	82	6.85	21	15.11	2.52	270	108	23.86	402
18	32	133	79	6.62	21	14.15	2.40	256	102	21.42	379
17	33	129	62	5.60	21	13.11	2.22	233	93	19.10	345
16	34	121	59	5.42	21	12.05	2.10	220	88	16.92	325
15	36	114	56	5.00	21	10.91	1.92	209	84	14.88	308
14	37	92	55	4.80	21	10.52	1.80	186	74	12.96	273
13	38	90	53	4.67	21	9.36	1.62	180	72	11.18	263
12	38	86	29	4.42	21	8.49	1.50	149	60	9.52	219
11	39	84	29	4.31	21	7.39	1.30	146	58	8.00	212
10	38	84	29	4.31	21	6.56	1.20	146	58	6.62	211
9	37	84	29	4.31	21	5.52	1.02	146	58	5.36	211

SUMMARY OF ESTIMATED BASIC COSTS OF TUNNEL EXCAVATION
(continued)

Unlined tunnel diameter in feet	Rate of heading advance in feet per 24-hour day	Labor dollars per foot	Underground equipment dollars per foot	Power dollars per foot	Expendable materials: Pipe track etc. dollars per foot	Expendable materials: Explosives dollars per foot	Expendable materials: Drill bits and rods dollars per foot	Subtotal dollars per foot	15% profit 25% contingencies dollars per foot	Miscellaneous items* dollars per foot	Total cost of excavation dollars per foot
Dry Headings in Completely Crushed or Unconsolidated Sediments											
24	10	485	259	21.33	21	Assume	Assume	786	314	38.08	1,138
23	11	441	235	19.20	21	none or	none or	716	286	34.98	1,037
22	12	380	213	19.20	21	very	very	633	253	32.00	918
21	13	350	197	18.36	21	minor	minor	586	234	29.16	849
20	14	315	182	16.00	21	amount	amount	534	214	26.44	774
19	15	294	170	14.77	21	required	required	500	200	23.86	724
18	16	266	158	13.71	21			459	184	21.42	669
17	17	251	120	11.20	21			403	161	19.10	583
16	18	228	113	10.50	21			373	149	16.92	539
15	19	216	107	9.88	21			354	142	14.88	511
14	20	170	101	8.84	21			301	120	12.96	434
13	21	162	96	8.00	21			287	115	11.18	413
12	23	142	48	7.30	21			218	87	9.52	315
11	24	136	46	7.00	21			210	84	8.00	302
10	23	135	37	7.00	21			200	80	6.62	287
9	21	135	37	7.00	21			200	80	5.36	287

SUMMARY OF ESTIMATED BASIC COSTS OF TUNNEL EXCAVATION
(continued)

Unlined tunnel diameter in feet	Rate of heading advance in feet per 24-hour day	Labor dollars per foot	Underground equipment dollars per foot	Power dollars per foot	Expendable materials: Pipe track etc. dollars per foot	Expendable materials: Explosives dollars per foot	Expendable materials: Drill bits and rods dollars per foot	Subtotal dollars per foot	15% profit 25% contingencies dollars per foot	Miscellaneous items* dollars per foot	Grout dollars per foot	Total cost of excavation dollars per foot
						Wet Headings in Competent Rock						
24	8	606	323	24.00	21	26.33	3.30	1,003	401	38.08	100	1,542
23	9	539	287	21.33	21	24.56	3.12	896	358	34.98	100	1,389
22	9	506	284	21.33	21	23.08	3.00	858	343	32.00	100	1,333
21	10	456	256	19.20	21	21.41	2.82	776	310	29.16	100	1,215
20	10	441	254	19.20	21	20.02	2.70	758	303	26.44	100	1,187
19	11	401	231	18.36	21	18.41	2.52	692	277	23.86	100	1,093
18	11	387	230	18.36	21	17.12	2.40	676	270	21.42	100	1,067
17	12	355	171	14.00	21	15.87	2.22	579	231	19.10	100	929
16	12	343	169	14.00	21	14.39	2.10	563	225	16.92	100	905
15	13	316	156	12.92	21	12.96	1.92	521	208	14.88	100	844
14	14	243	144	12.00	21	12.67	1.80	434	174	12.96	100	721
13	15	227	135	11.20	21	11.22	1.62	407	163	11.18	100	681
12	15	217	74	11.20	21	10.06	1.50	335	134	9.52	100	574
11	15	217	74	11.20	21	8.71	1.32	333	133	8.00	100	574
10	14	217	74	11.20	21	7.67	1.20	332	133	6.62	100	572
9	14	217	74	11.20	21	6.42	1.02	330	132	5.36	100	567

SUMMARY OF ESTIMATED BASIC COSTS OF TUNNEL EXCAVATION
(continued)

Unlined tunnel diameter in feet	Rate of heading advance in feet per 24-hour day	Labor dollars per foot	Under-ground equipment dollars per foot	Power dollars per foot	Expendable Materials: Pipe track etc. dollars per foot	Expendable Materials: Explosives dollars per foot	Expendable Materials: Drill bits and rods dollars per foot	Subtotal dollars per foot	15% profit 25% contingencies dollars per foot	Miscellaneous items* dollars per foot	Total cost of excavation dollars per foot
Wet Headings in Crushed Rock or Unconsolidated Sediments											
24	3	1,617	862	64.00	21	Assume	Assume	2,564	1,026	38.08	3,628
23	3	1,617	862	64.00	21	none or	none or	2,564	1,026	34.98	3,625
22	4	1,139	639	48.00	21	very	very	1,874	750	32.00	2,656
21	4	1,139	639	48.00	21	minor	minor	1,874	750	29.16	2,653
20	5	882	509	38.40	21	amount	amount	1,450	580	26.44	2,056
19	5	882	509	38.40	21	required	required	1,450	580	23.86	2,054
18	6	710	422	32.00	21			1,205	482	21.42	1,708
17	6	710	341	32.00	21			1,104	441	19.10	1,564
16	6	685	339	28.00	21			1,073	429	16.92	1,519
15	7	587	290	24.00	21			922	369	14.88	1,306
14	7	487	288	24.00	21			820	328	12.76	1,161
13	8	426	252	21.00	21			720	288	11.18	1,019
12	8	407	139	21.00	21			588	235	9.52	833
11	8	407	139	21.00	21			588	235	8.00	831
10	7	407	139	21.00	21			588	235	6.62	830
9	6	407	139	21.00	21			588	235	5.36	828

*Estimated on a basis of two dollars per cubic yard of excavation which includes allowance for profit and contingencies.

TABLE 7

ESTIMATED ROCK LOAD

Rock load H_p in feet of rock on roof of support in tunnel

with width B (ft) and height H_t (ft) at depth of more than $1.5\,(B + H_t)$.[1]

Rock Condition	*Rock Load H_p in feet*	*Remarks*
1. Hard and intact	zero	Light lining, required only if spalling or popping occurs.
2. Hard stratified or schistose[2]	0 to 0.5 B	Light support. See *Fig. 38.*
3. Massive, moderately jointed	0 to 0.25 B	Load may change erratically from point to point.
4. Moderately blocky and seamy	0.25 B to $0.35\,(B + H_t)$	No side pressure. See *Fig. 39.*
5. Very blocky and seamy	$(0.35$ to $1.10)\,(B + H_t)$	Little or no side pressure. See *Fig. 40.*
6. Completely crushed but chemically intact	$1.10\,(B + H_t)$	Considerable side pressure. Softening effect of seepage towards bottom of tunnel requires either continuous support for lower ends of ribs *(Fig. 41)* or circular ribs *(Fig. 42).*
7. Squeezing rock, moderate depth	$(1.10$ to $2.10)\,(B + H_t)$	Heavy side pressure, invert struts re-
8. Squeezing rock, great depth	$(2.10$ to $4.50)\,(B + H_t)$	quired. Circular ribs are recommended.
9. Swelling rock	Up to 250 ft. irrespective of value of $(B + H_t)$	Circular ribs required. In extreme cases use yielding support.

1. The roof of the tunnel is assumed to be located below the water table. If it is located permanently above the water table, the values given for types 4 to 6 can be reduced by fifty per cent.

2. Some of the most common rock formations contain layers of shale. In an unweathered state, real shales are no worse than other stratified rocks. However, the term shale is often applied to firmly compacted clay sediments which have not yet acquired the properties of rock. Such so-called shale may behave in the tunnel like squeezing or even swelling rock.

If a rock formation consists of a sequence of horizontal layers of sandstone or limestone and of immature shale, the excavation of the tunnel is commonly associated with a gradual compression of the rock on both sides of the tunnel, involving a downward movement of the roof. Furthermore, the relatively low resistance against slippage at the boundaries between the so-called shale and rock is likely to reduce very considerably the capacity of the rock located above the roof to bridge. Hence, in such rock formations, the roof pressure may be as heavy as in a very blocky and seamy rock.

NOTE:

From "Rock Tunneling With Steel Support, by Proctor and White With introduction by Karl Terzaghi. Published by Commercial Shearing and Stamping Company of Youngstown, Ohio. Reproduced with permission of the publisher.

TABLE 8

FIELD NOTES ON GEOLOGIC EXAMINATION OF TUNNEL ALIGNMENTS

FROM STATION	TO STATION	DISTANCE BETWEEN STATIONS IN FEET	ROCK TYPES PRESENT	ROCK CONDITIONS AFFECTING COST OF EXCAVATION & LAGGING — DRY HEADINGS: HARD INTACT OR MASSIVE MODERATELY JOINTED	DRY HEADINGS: STRATIFIED OR SCHISTOSE	DRY HEADINGS: MODERATELY BLOCKY & SEAMY	DRY HEADINGS: VERY BLOCKY & SEAMY	DRY HEADINGS: UNCONSOLIDATED SEDIMENTS OR COMPLETELY CRUSHED CHEMICALLY INTACT	WET HEADINGS: COMPETENT ROCK	WET HEADINGS: CRUSHED OR UNCONSOLIDATED MATERIAL	GROUND WATER: ESTIMATED FLOW LOW MEDIUM HEAVY	GROUND WATER: POSSIBLE PRESSURE HEAD	FACTORS AFFECTING COST OF SUPPORT: ROCK DENSITY LBS/CU.FT	FACTORS AFFECTING COST OF SUPPORT: ESTIMATED ROCK LOAD	FACTORS AFFECTING COST OF SUPPORT: RIB SPACING	MAXIMUM DEPTH OF COVER	REMARKS
0+00	8+95	895	Granite			895 feet							170	0.5B	6 feet	300 feet	Granite - fresh and hard.
8+95	9+95	100	Fault zone - completely crushed granite and sandstone							100 feet	Medium	250 feet	150	$1.1(B+H_t)$	2 feet	250 feet	Alignment of springs along fault indicate wet conditions. Estimate moderate water inflows. Invert strut will probably be required.
9+95	37+95	2,800	Sandstone		2,800 feet								160	0.5B	6 feet	500 feet	Sandstone - moderately hard and impermeable. Individual beds average three feet in thickness. Negligible water inflows might be encountered along bedding planes.
37+95	44+00	605	Shale				605 feet						160	$0.6(B+H_t)$	4 feet	200 feet	Badly fractured clay shales that will probably squeeze. Invert strut will probably be required.

TABLE 9

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
SOUTHERN CALIFORNIA DISTRICT
ESTIMATED COST OF TUNNEL CONSTRUCTION

Name of Tunnel Sample — Bore Size: Unlined 24

Location In Subsistence Area — Lined 19.5

Computed by J. Doe

Date January, 1957

A. Basic Excavation Cost

	No. of lineal feet	Excavation cost/ft.	Subsistence cost/ft.	Cost
Dry Headings (Plate 8)				
Hard intact or massive moderately jointed				
Stratified or schistose	2,800	$460	$32	$1,377,600
Moderately blocky and seamy	895	485	34	464,505
Very blocky and seamy	605	505	37	327,910
Unconsolidated sediments of completely crushed				
Wet Headings (Plate 9)				
Competent rock				
Unconsolidated sediments or completely crushed	100	3,530	320	385,000
Subtotal A. Basic Excavation Cost				$2,555,015

Check subsistence map (Plate 7)
If subsistence required add cost from (Table 3)

TABLE 9

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
SOUTHERN CALIFORNIA DISTRICT
ESTIMATED COST OF TUNNEL CONSTRUCTION

Name of Tunnel Sample

Bore Size: Unlined 24

Location In Subsistence Area

Lined 19.5

Computed by J. Doe

Date January, 1957

A. Basic Excavation Cost

	No. of lineal feet	Excavation cost/ft.	Subsistence cost/ft.	Cost
Dry Headings (Plate 8)				
Hard intact or massive moderately jointed				
Stratified or schistose	2,800	$460	$32	$1,377,600
Moderately blocky and seamy	895	485	34	464,505
Very blocky and seamy	605	505	37	327,910
Unconsolidated sediments of completely crushed				
Wet Headings (Plate 9)				
Competent rock				
Unconsolidated sediments or completely crushed	100	3,530	320	385,000
		Subtotal A. Basic Excavation Cost		$2,555,015

Check subsistence map (Plate 7)
If subsistence required add cost from (Table 3)

ESTIMATED COST OF TUNNEL CONSTRUCTION
(continued)

B. Dewatering Cost

	Max. no. of ft. to portal	Pipe cost per foot	Pipe cost	Pump cost	Cost
Pump and pipe costs for dewatering headings in unconsolidated sediments or crushed zones (Plate 9)					
Low inflow 100-500 gpm					
Moderate inflow 500-1500 gpm	995	$6.00	$5,970	$6,000	$11,970
High inflow 1500-20,000 gpm					

Subtotal B. Dewatering Cost $11,970

C. Steel Support Cost

Steel Support (Plates 10 - 14)

No. of feet	Estimated rock load	Rib spacing	No. of sets	Cost per foot	Cost
3,695	0.5 B	6' Continuous rib without invert	616	$ 75.00	$277,125
605	$0.60(B+H_t)$	4' Continuous rib with invert	151	262.50	158,812
100	$1.10(B+H_t)$	2' Rib, wall plate and post with invert strut	50	565.00	56,500

Subtotal C. Steel Support Cost $492,437

ESTIMATED COST OF TUNNEL CONSTRUCTION
(continued)

D. Cost of Foot Blocks

	No. of sets	Cost/set	Cost
Cost of Foot Blocks (Plates 10 - 14)	817	$3.10	$2,533

Subtotal D. Cost of Foot Blocks $2,533

E. Timber Lagging and Support Cost

	No. of feet	Cost/ft.	Cost
Lagging (Plate 15)			
Massive, moderately jointed; moderately blocky and seamy; and stratified or schistose	3,695	$ 22.00	$81,290
Very blocky and seamy	605	42.50	25,712
Unconsolidated sediments or completely crushed material (horseshoe section)	100	78.00	7,800
Timber Support (Plate 16) Multiple drift	100	162.50	16,250
Note: Use for wet crushed or unconsolidated or dry crushed and unconsolidated sediments over 16 feet unlined in diameter. Steel cost is also applied as well as timber			

Subtotal E. Timber Lagging and Support Cost $131,052

ESTIMATED COST OF TUNNEL CONSTRUCTION
(continued)

F. Concrete Lining Cost

	No. of feet	Cost/ft.	Total cost
Concrete Lining (Plate 17 - 19)			
Horseshoe Rib - Horseshoe Section	4,400	$315	$1,386,000
Horseshoe Rib - Circular Section			
Circular Rib - Circular Section			
No rib - Horseshoe Section			
No rib - Circular Section			

Subtotal F. Concrete Lining Cost $1,386,000

G. Appurtenant Tunnel Construction Facilities

	Total cost
Access Roads	
Construction	$ 50,000
Maintenance	2,000
Power Supply	
Installation of power lines	25,000
Construction of generating plant if power line installation not feasible	
Surface Buildings	22,000
Construction Camp (if needed)	
Portal Excavation and Construction	65,000
Water Supply	7,000
Sewer System	

Subtotal G. Appurtenant Tunnel Construction Facilities $ 171,000

Total Estimated Cost of Tunnel $4,750,000

TABLE 10

RIB SPACING*

Rock condition	Estimated rock load	Customary rib spacing
Hard and intact	0	Steel support usually not required.
Massive, moderately jointed	0-0.25B	Some intervals will not require steel support, depending on rock load. Ribs on 6-foot centers where used.
Stratified or schistose	0-0.5B	Some intervals will not require steel support, depending on rock load. Ribs on 6-foot centers where used.
Moderately blocky and seamy	$0.25B-0.35(B+H_t)$	Rib spacing on 6-foot centers for lighter rock loads and on 4-foot centers for heavier rock loads.
Very blocky and seamy	$0.35(B+H_t)-1.10(B+H_t)$	Rib spacing on 4-foot centers for lighter rock loads and on 2-foot centers for heavier rock loads.
Unconsolidated or completely crushed	$1.10(B+H_t)$	Rib spacing on 2-foot centers.
Squeezing ground	Rock loads in excess of $1.10(B+H_t)$	Rib spacing on 2-foot centers or less.
Wet, competent rock	Rock loads variable, may fall in any of the above classifications except unconsolidated or completely crushed.	Refer to appropriate classification above.
Wet, unconsolidated or crushed materials	$1.10(B+H_t)$ or more.	Rib spacing on 2-foot centers or less.

*Note: Rib spacings cited in this table are spacings customarily used. Judgment must be applied in selecting rib spacing where unusual conditions prevail.

TABLE 11

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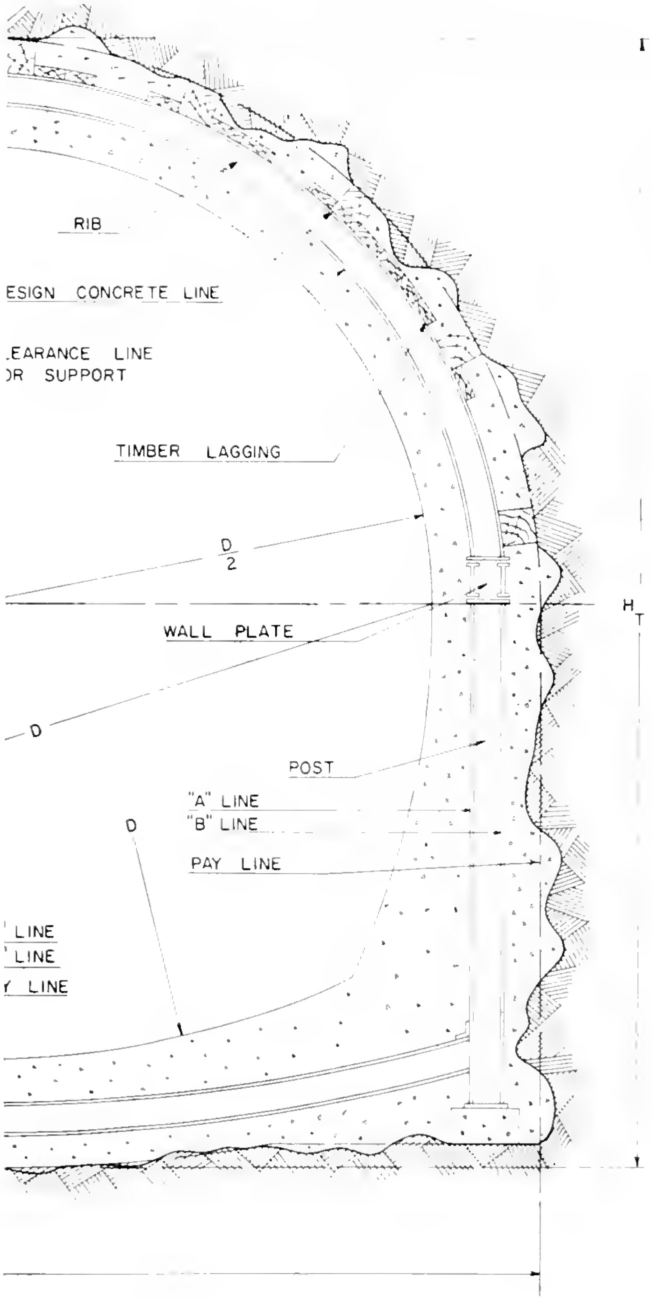
PLATES

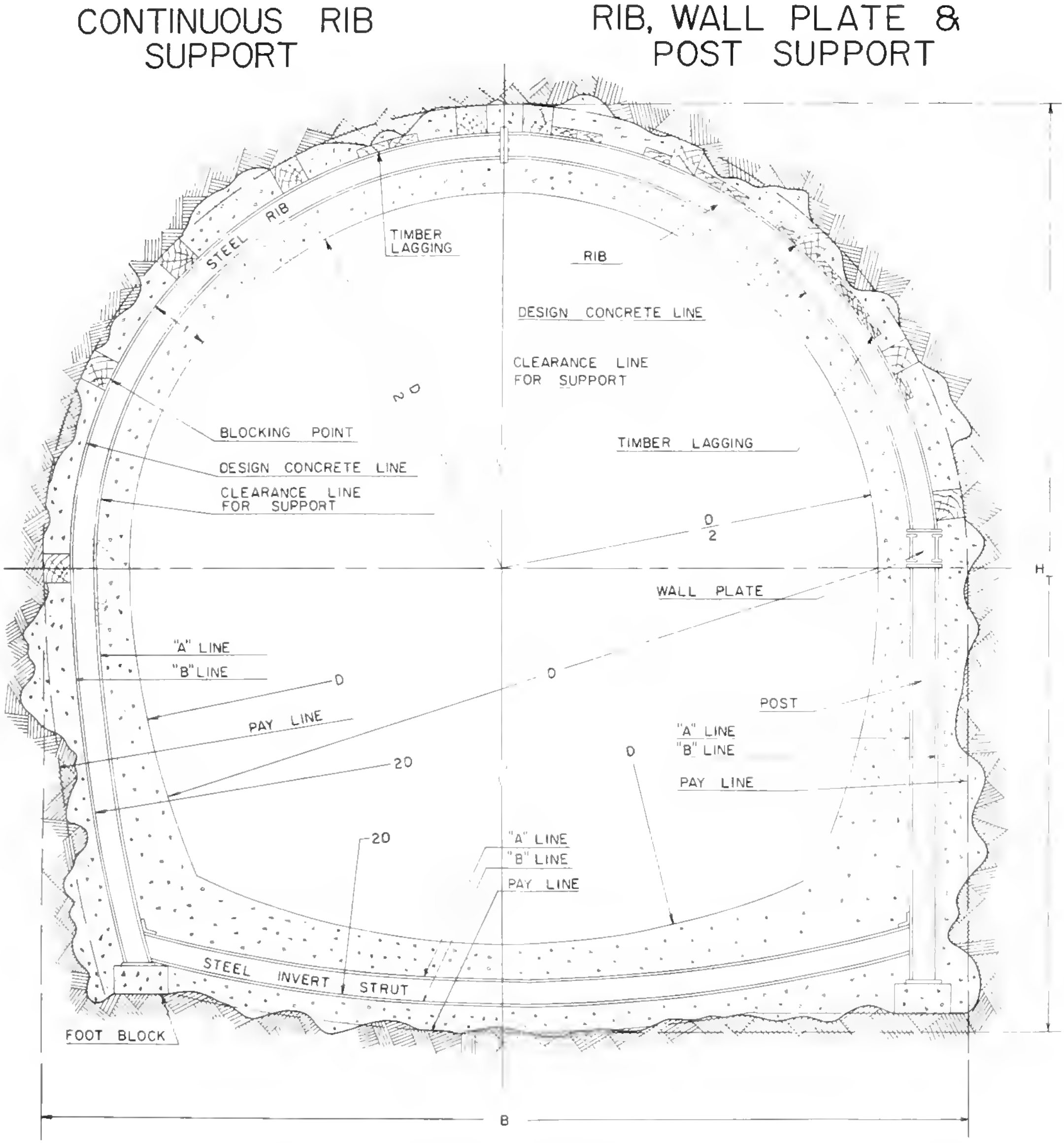
RIB, WALL PLATE & POST SUPPORT



?ROPERTIES
0.82 DEPTH

$35\ 3D^{8/3}\ S^{1/2}$
$0\ 7332\ D^{2}$
$0\ 3D66\ D$
$48\ 3D^{2/3}\ S^{1/2}$
$0\ 014$

N WITH HORSESHOE STEEL SUPPORT

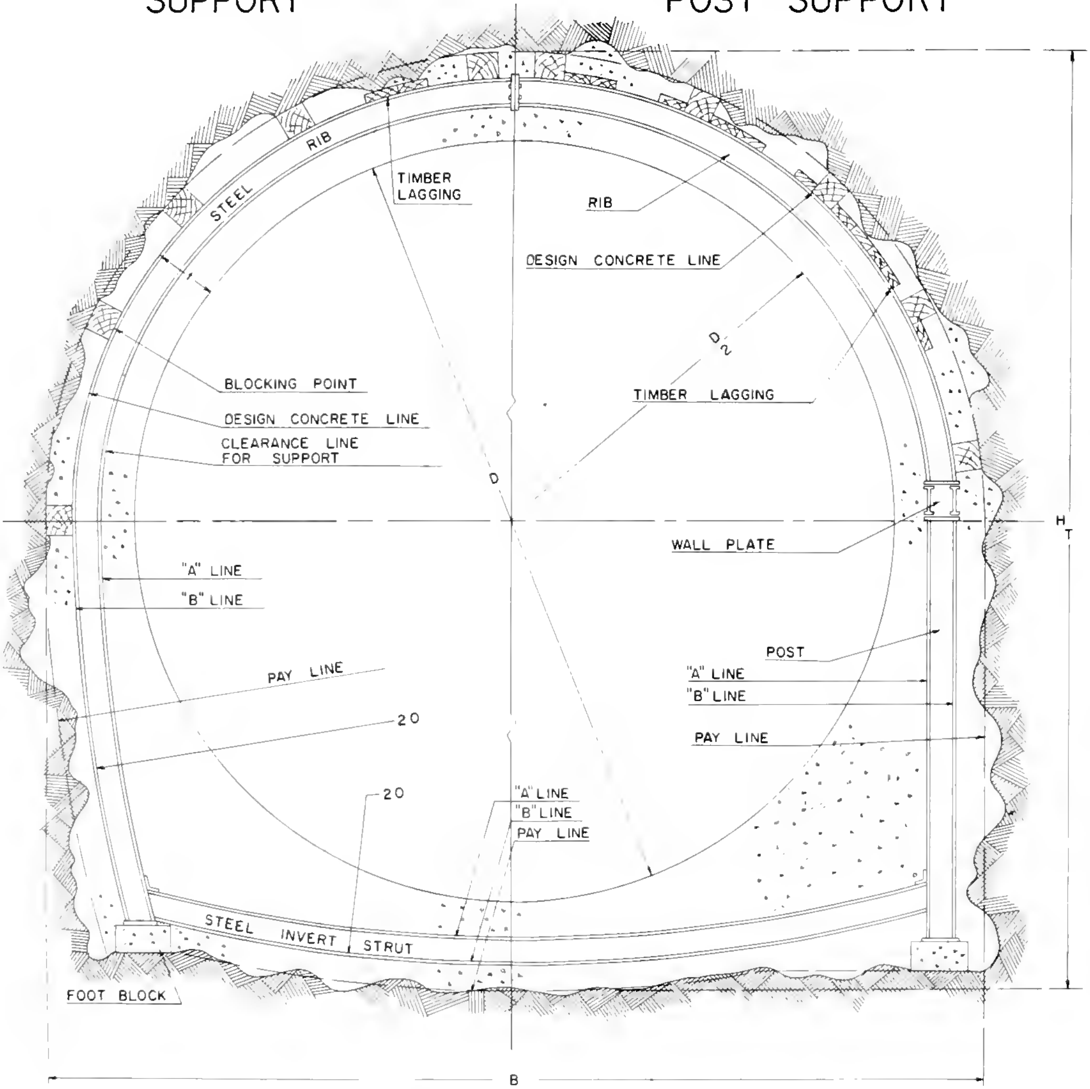


HYDRAULIC FULL	PROPERTIES 0.82 DEPTH
$Q-35\,30D^{8/3}S^{1/2}$	$35\,30D^{8/3}S^{1/2}$
$A-0\,8293\,D^{2}$	$0\,7332\,D^{2}$
$R-0\,2538\,D$	$0\,3066\,D$
$V-42\,60^{2/3}S^{1/2}$	$48\,3D^{2/3}S^{1/2}$
$n-0\,014$	$0\,014$

TYPICAL HORSESHOE TUNNEL SECTION WITH HORSESHOE STEEL SUPPORT

CONTINUOUS RIB SUPPORT

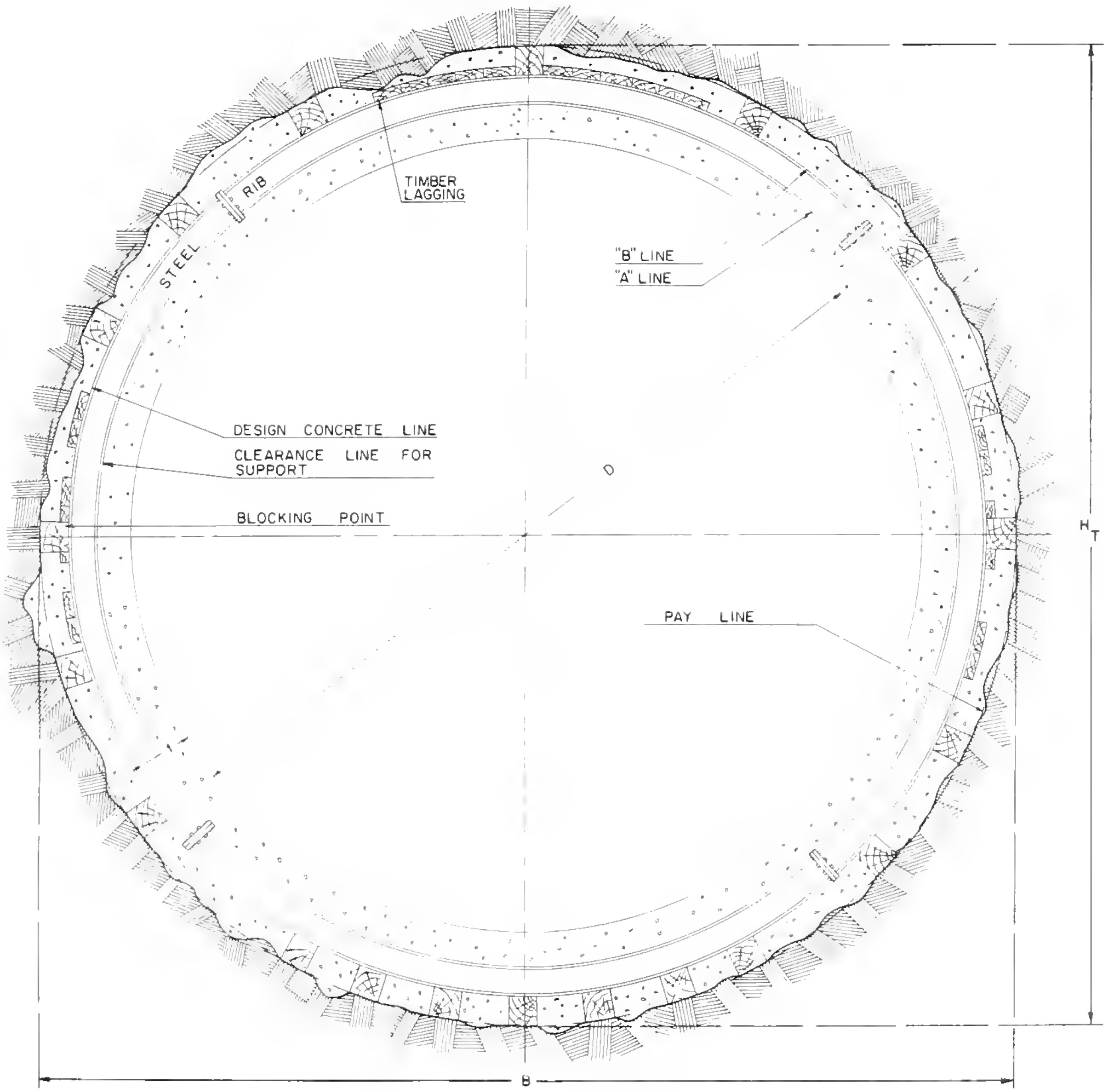
RIB, WALL PLATE & POST SUPPORT



HYDRAULIC PROPERTIES	
FULL	0.82 DEPTH
$Q - 3\,3050\,D^{8/3}\,S^{1/2}$	$3\,3050\,D^{8/3}\,S^{1/2}$
$A - 0\,7854\,D^{2}$	$0\,6893\,D^{2}$
$R - 0\,2500\,D$	$0\,3043\,D$
$V - 42\,08\,D^{2/3}\,S^{1/2}$	$47\,95\,D^{2/3}\,S^{1/2}$
$n - 0\,014$	$0\,014$

TYPICAL CIRCULAR TUNNEL SECTION
WITH HORSESHOE STEEL SUPPORT

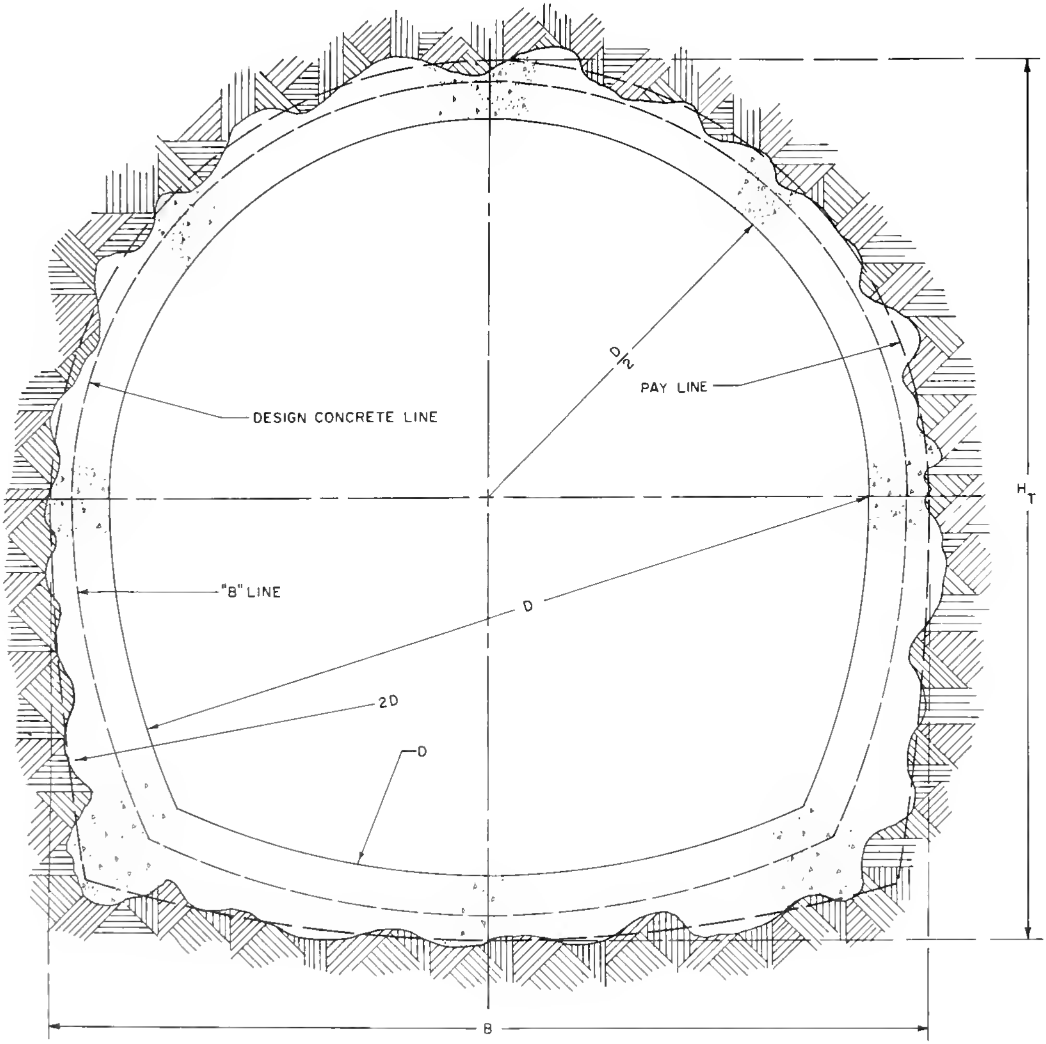
CIRCULAR SUPPORT



HYDRAULIC PROPERTIES FULL	0.82 DEPTH
Q-33 05 $D^{8/3}$ $S^{1/2}$	33 05 $D^{8/3}$ $S^{1/2}$
A-0 7854 D^2	0 6893 D^2
R-0 2500 D	0 3043 D
V-42 08 $D^{2/3}$ $S^{1/2}$	47 95 $D^{2/3}$ $S^{1/2}$
n- 0 014	0 014

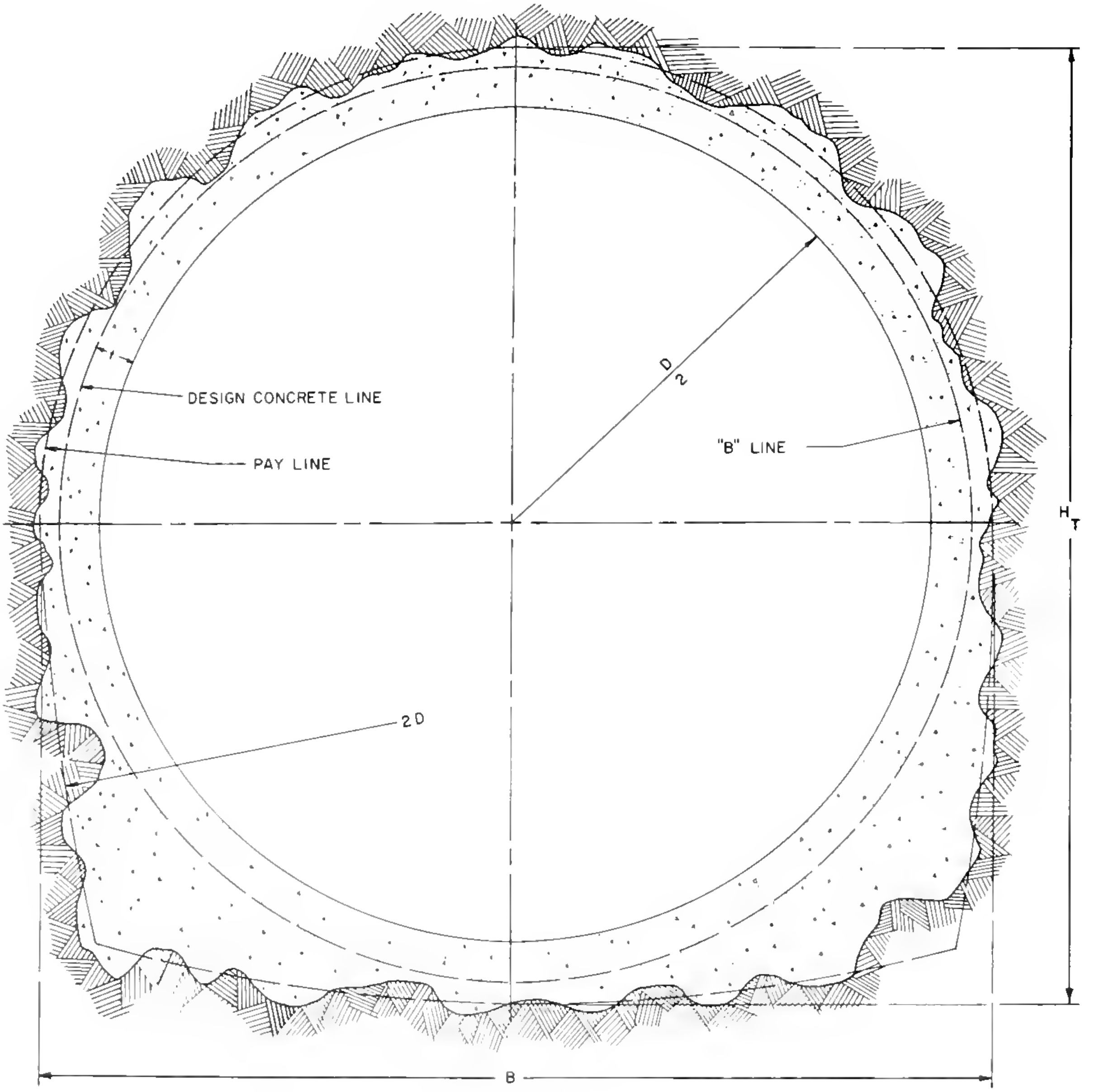
TYPICAL CIRCULAR TUNNEL SECTION
WITH CIRCULAR STEEL SUPPORT

DEPARTMENT OF WATER RESOURCES



HYDRAULIC	PROPERTIES
FULL	0.82 DEPTH
Q-35.3D S	35.3D S
A-0.8293D	0.7332D
R-0.2538D	0.3066D
V-42.6D S	48.3D S
n-0.014	0.014

TYPICAL HORSESHOE TUNNEL SECTION
WITHOUT STEEL SUPPORT



HYDRAULIC PROPERTIES

FULL	0.82 DEPTH
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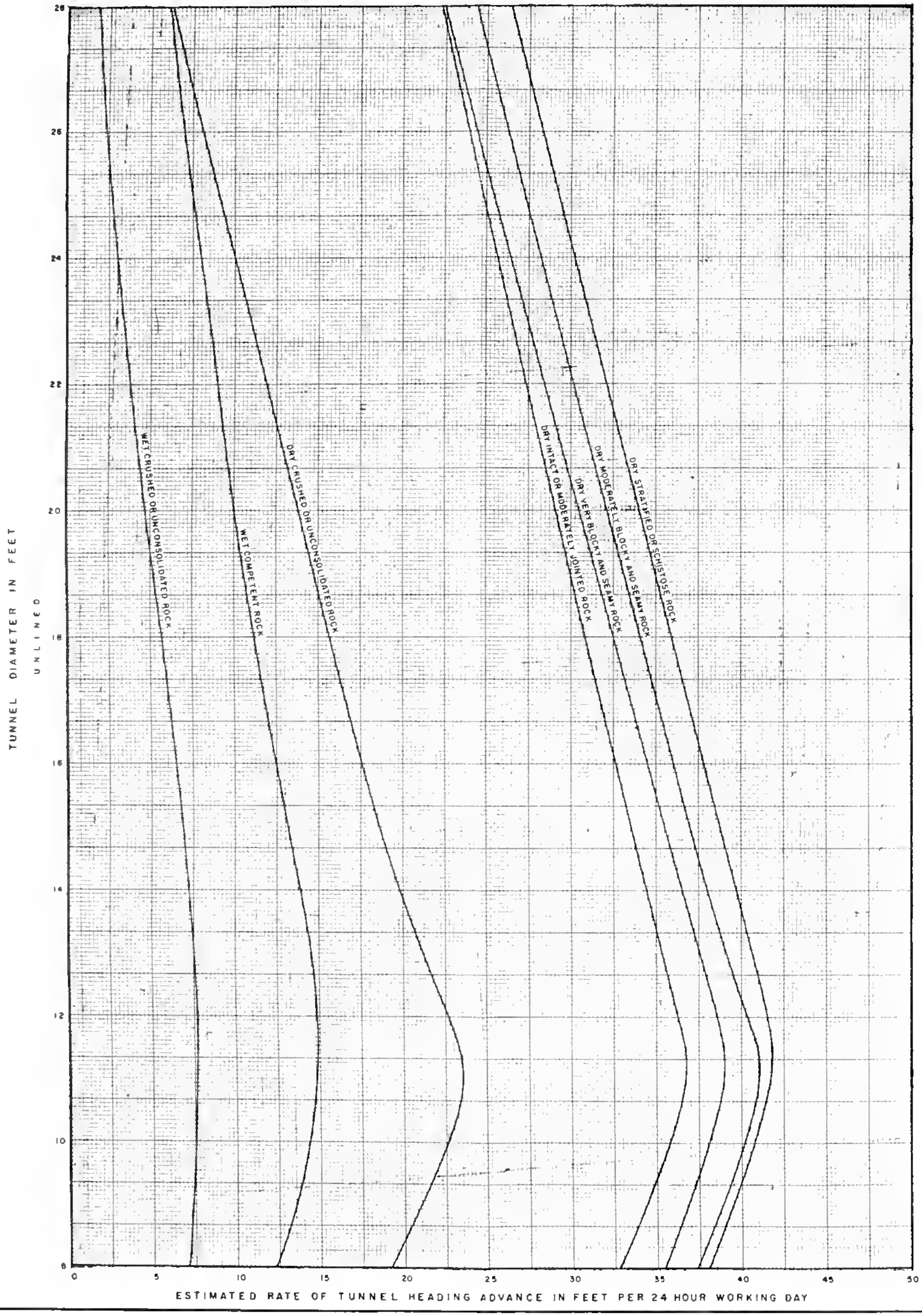
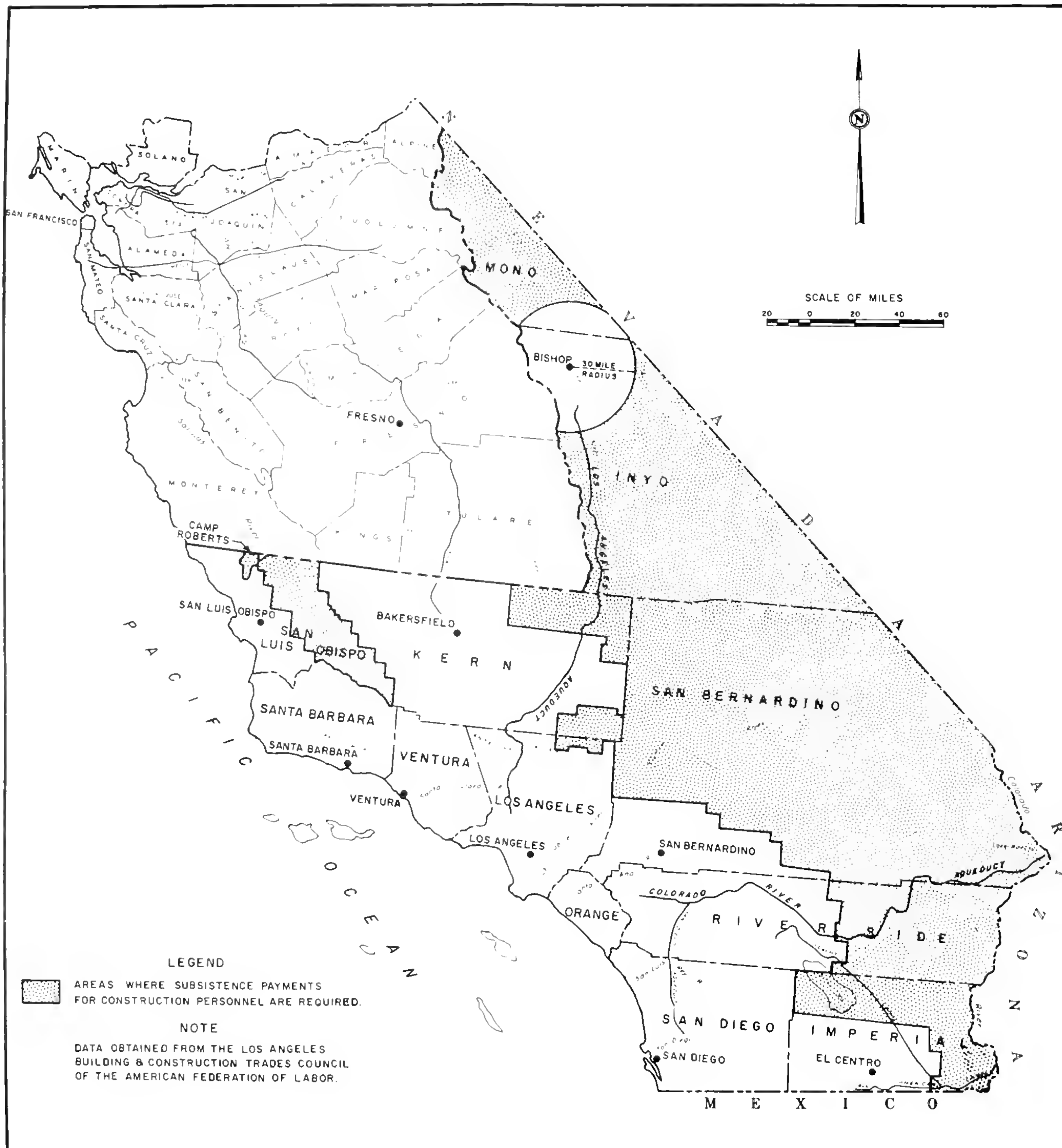
$A - 0.7854 D^2$	$0.6893 D^2$
$R - 0.2500 D$	$0.3043 D$
$V - 42.08 D^{2/3} S^{1/2}$	$47.95 D^{2/3} S^{1/2}$
$n - 0.014$	0.014

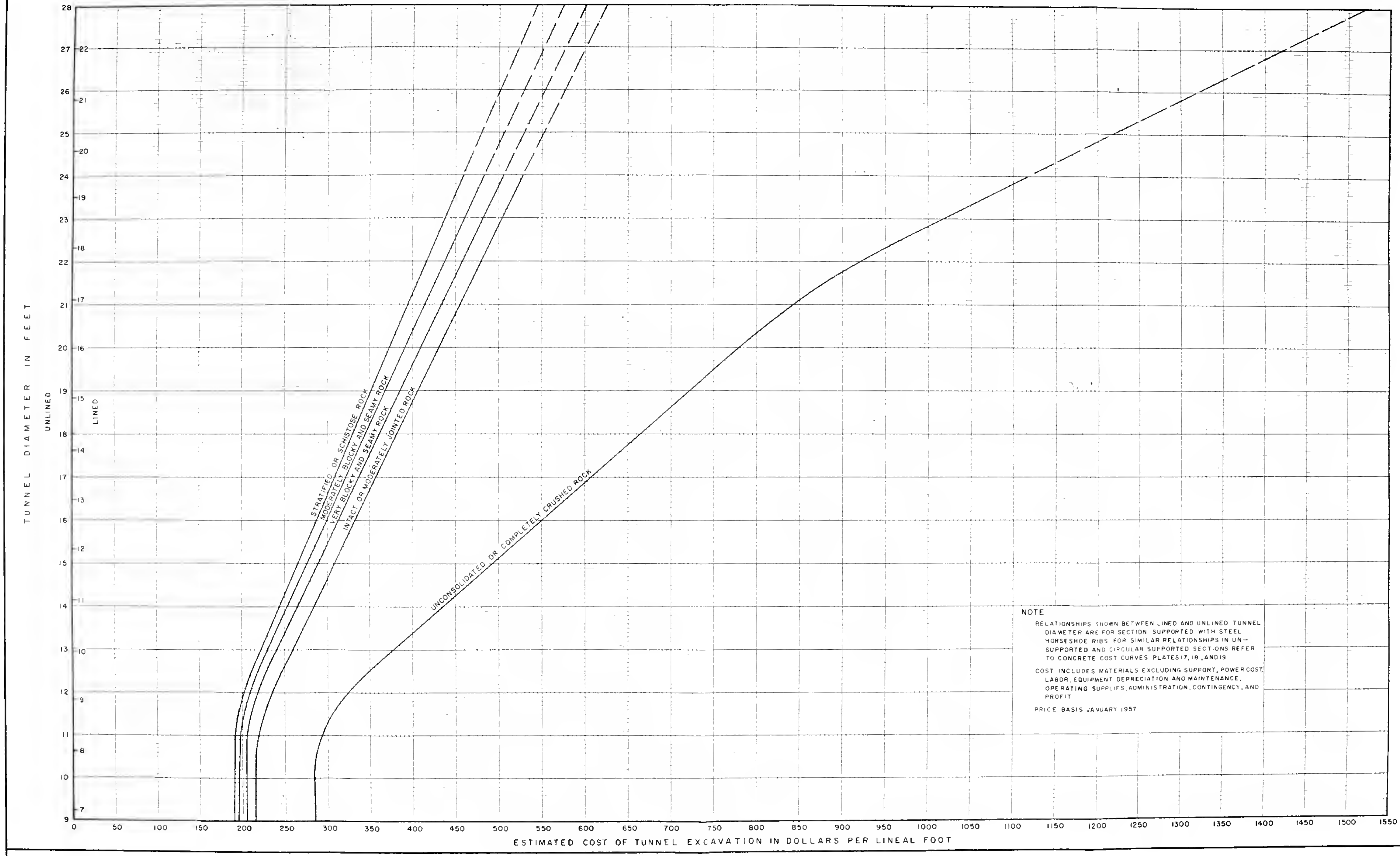
TYPICAL CIRCULAR TUNNEL SECTION
WITHOUT STEEL SUPPORT



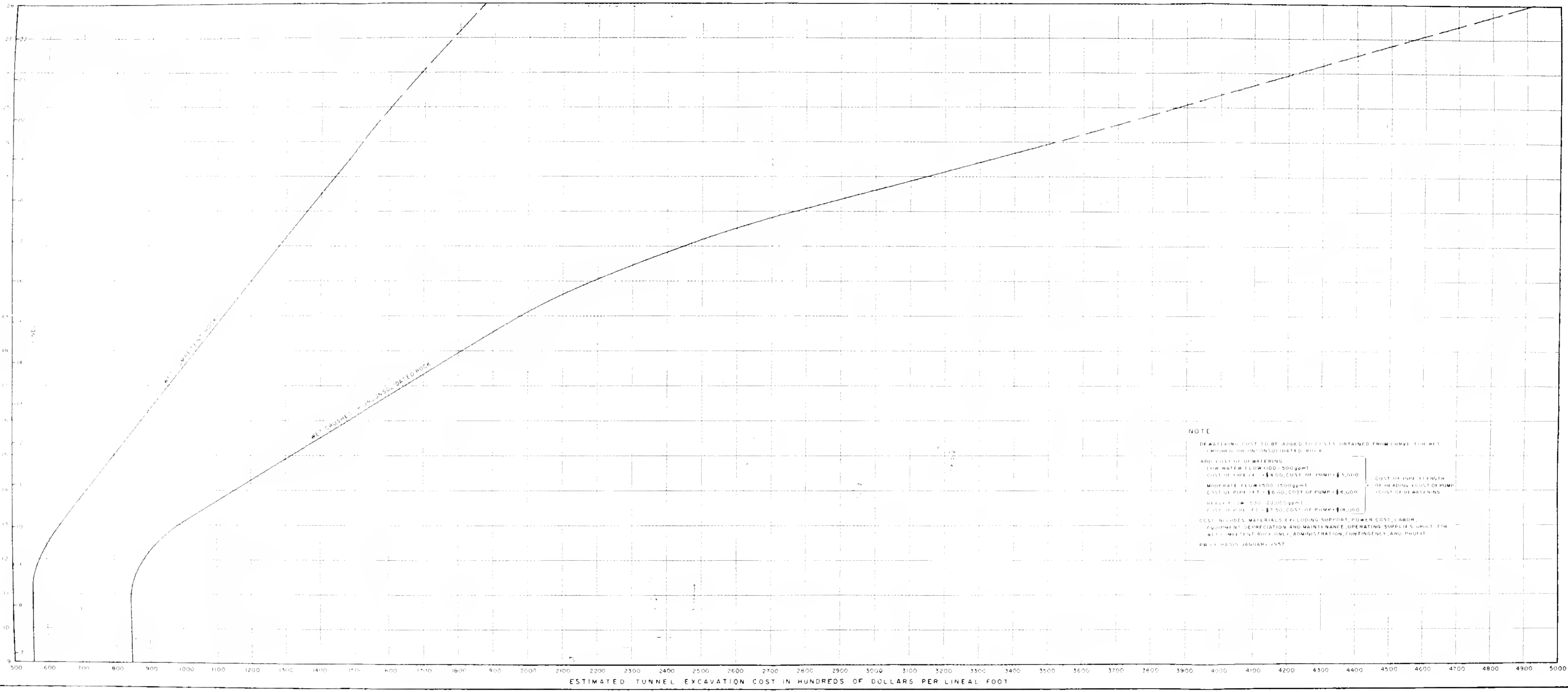
ESTIMATED RATES OF TUNNEL HEADING ADVANCE



SOUTHERN CALIFORNIA AREAS WHERE SUBSISTENCE PAYMENTS FOR CONSTRUCTION PERSONNEL ARE REQUIRED

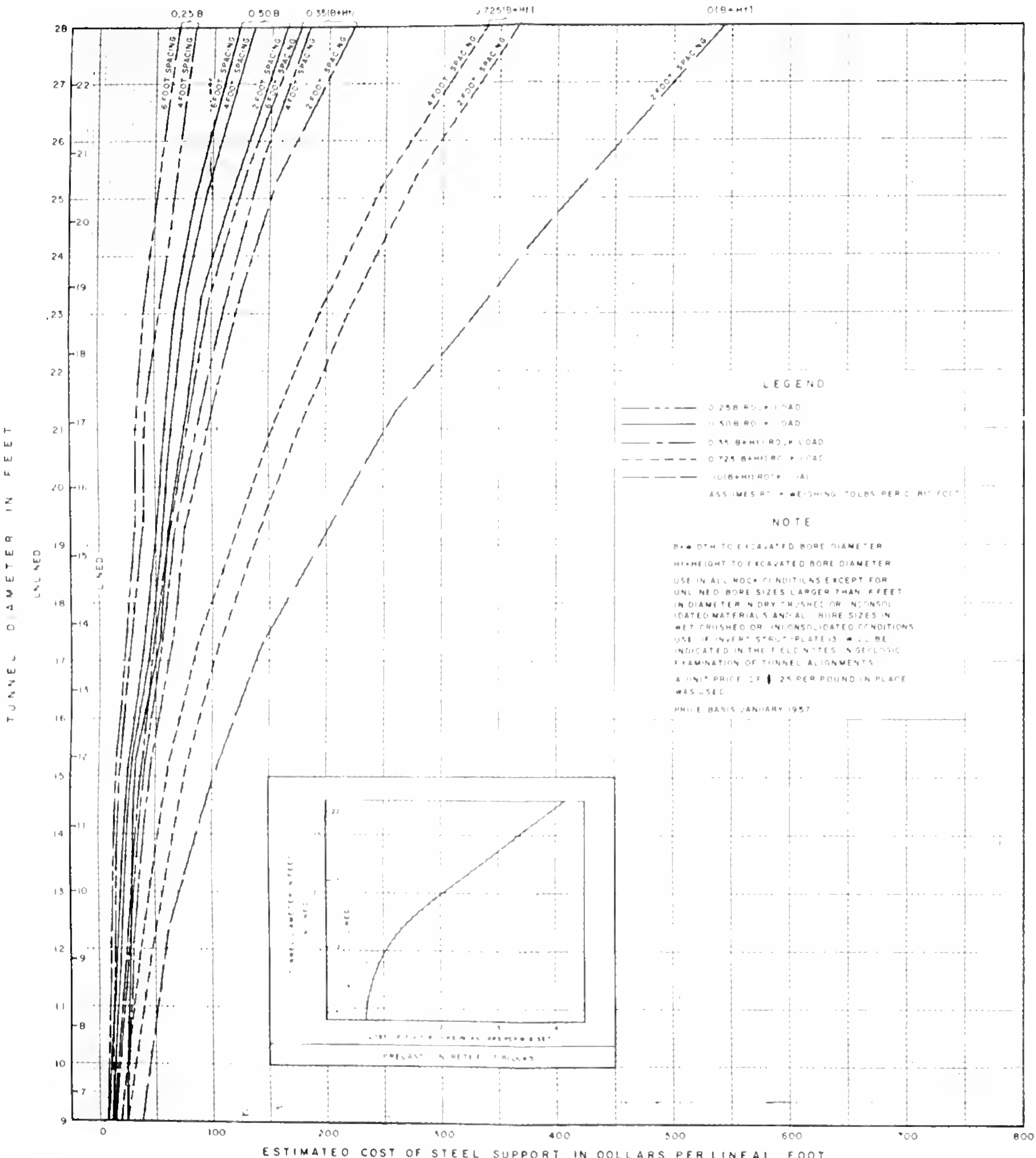


ESTIMATED BASIC TUNNEL EXCAVATION COSTS FOR DRY HEADINGS

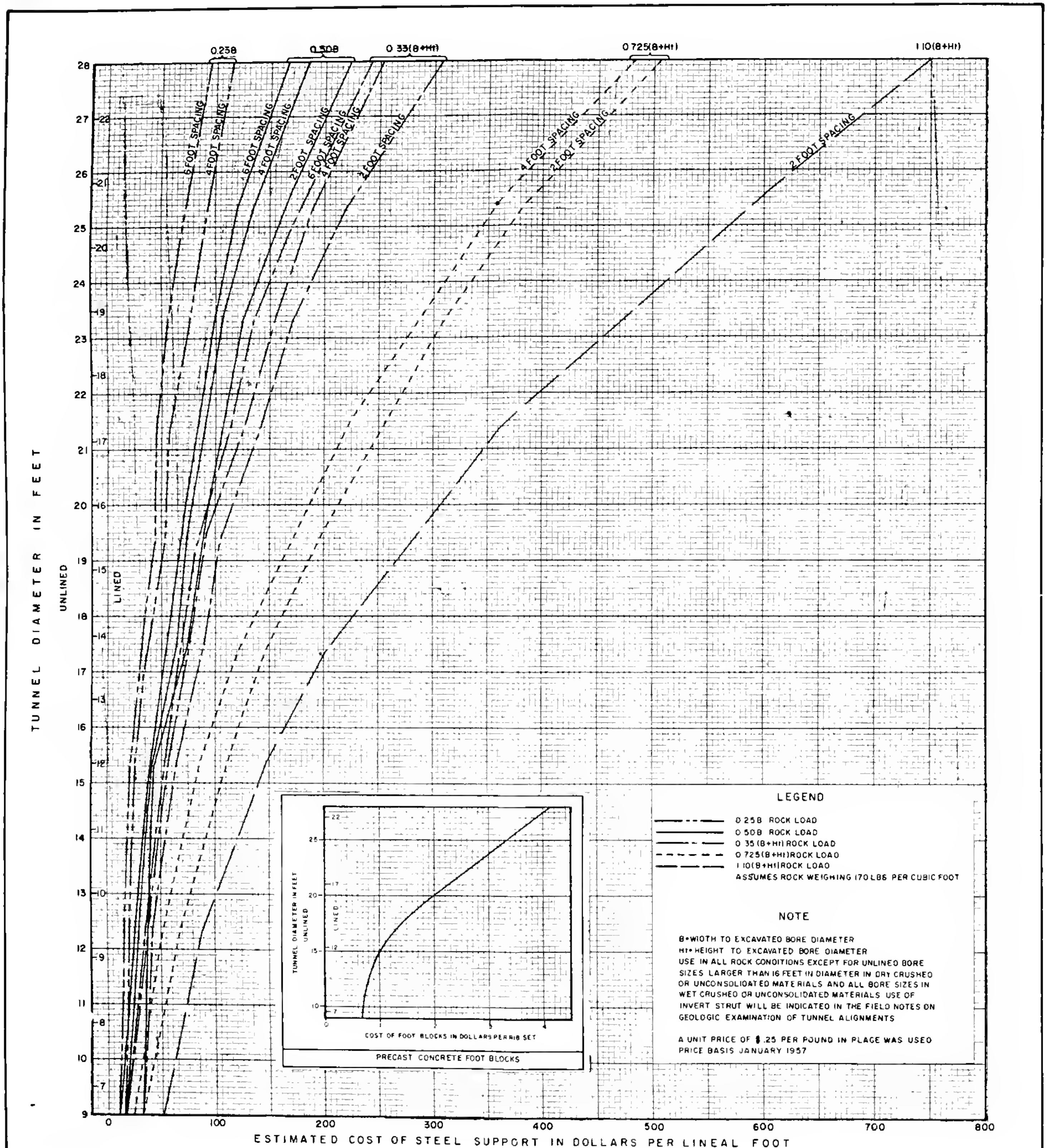


ESTIMATED BASIC TUNNEL EXCAVATION COSTS FOR WET HEADINGS

DEPARTMENT OF WATER RESOURCES



ESTIMATED COST OF STEEL SUPPORT CONTINUOUS HORSESHOE RIB WITHOUT INVERT STRUT



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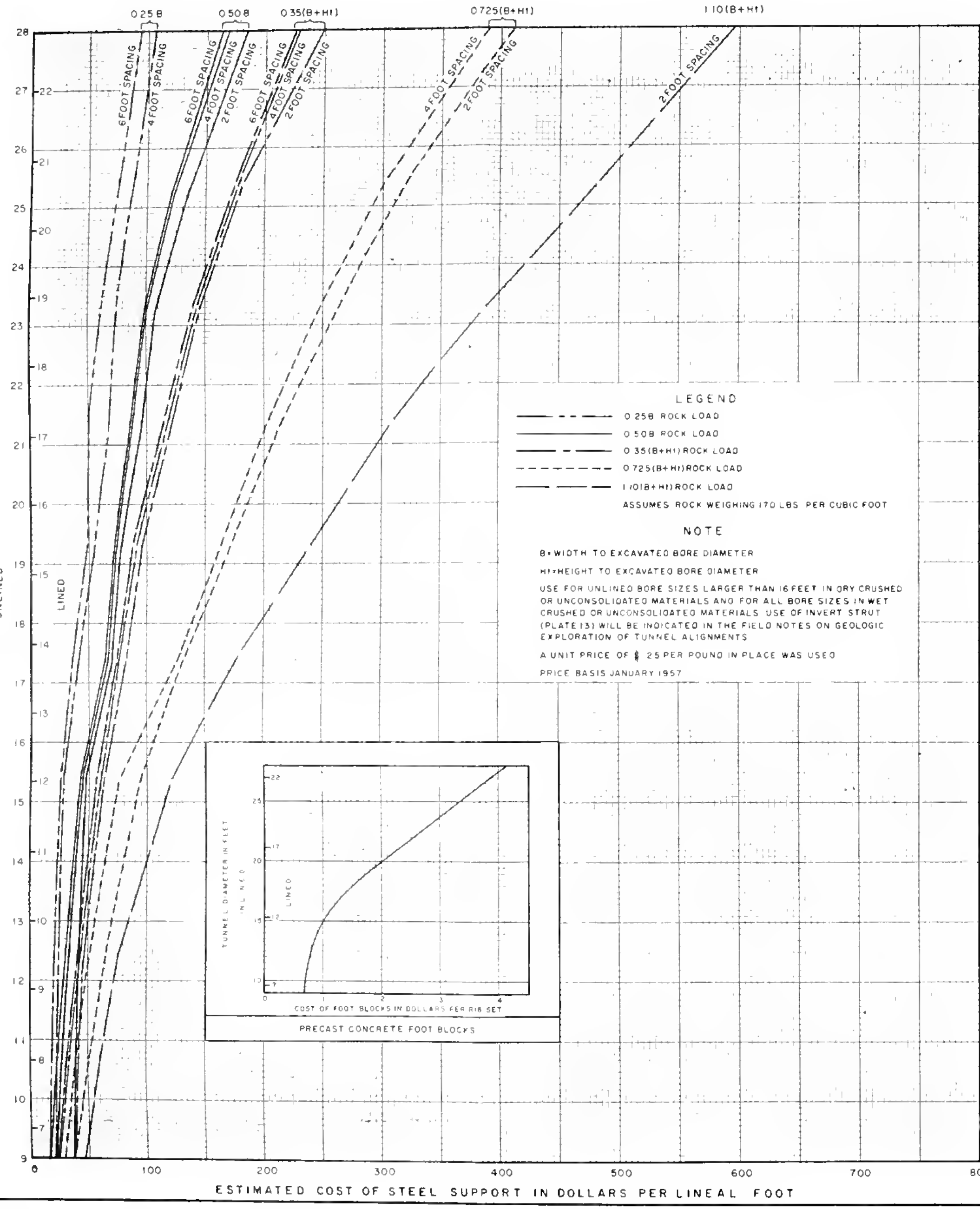

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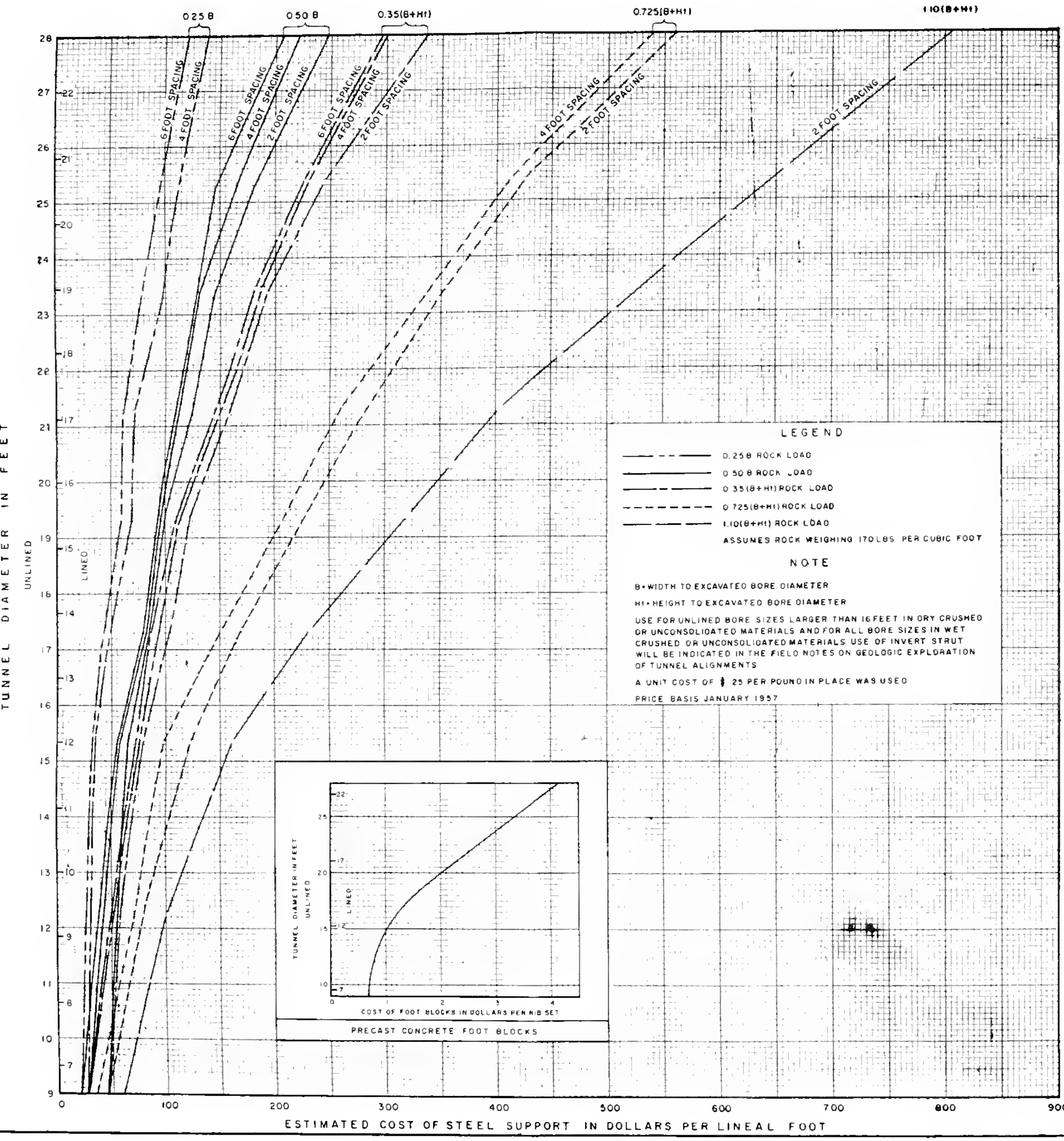

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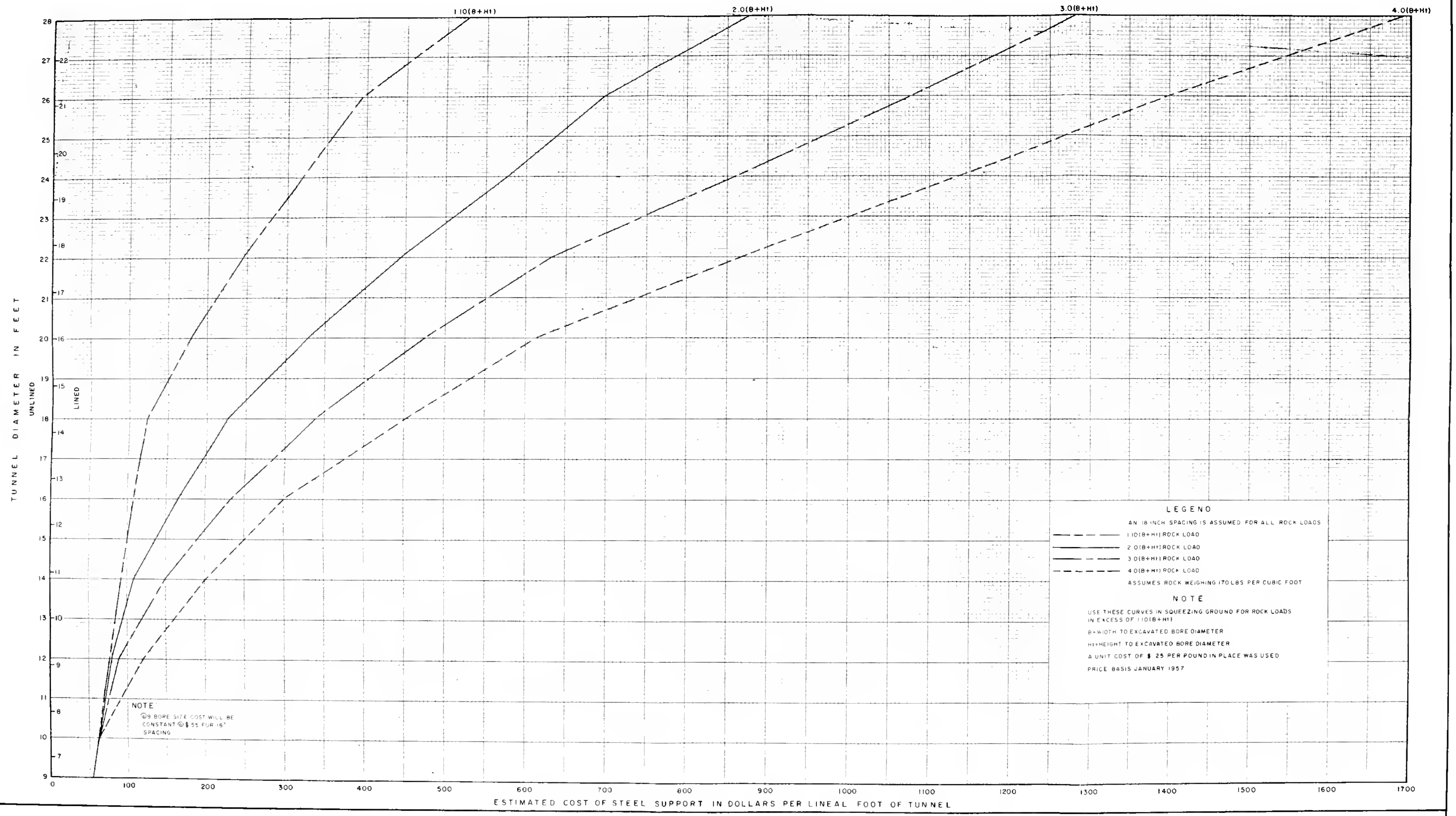

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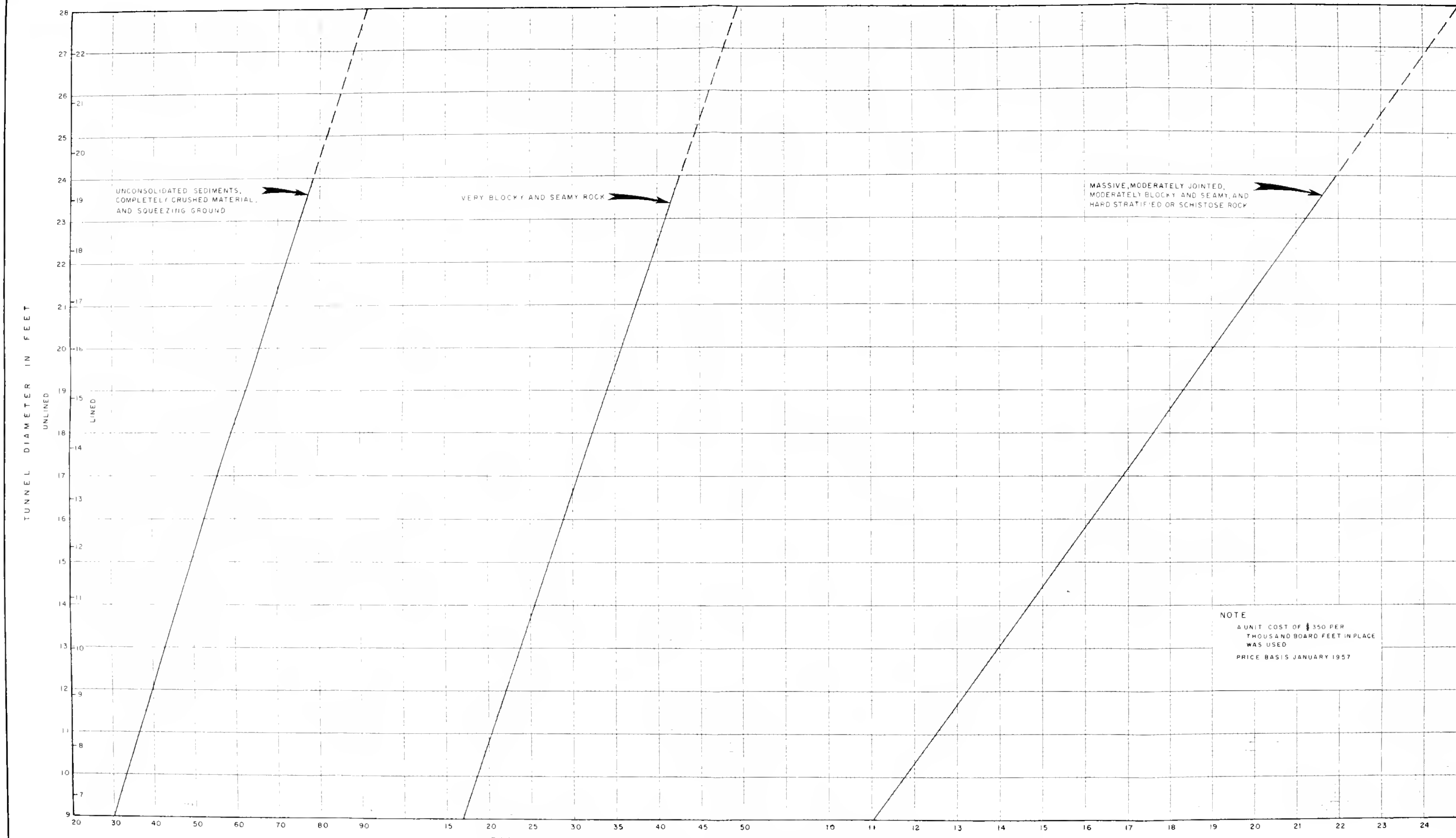

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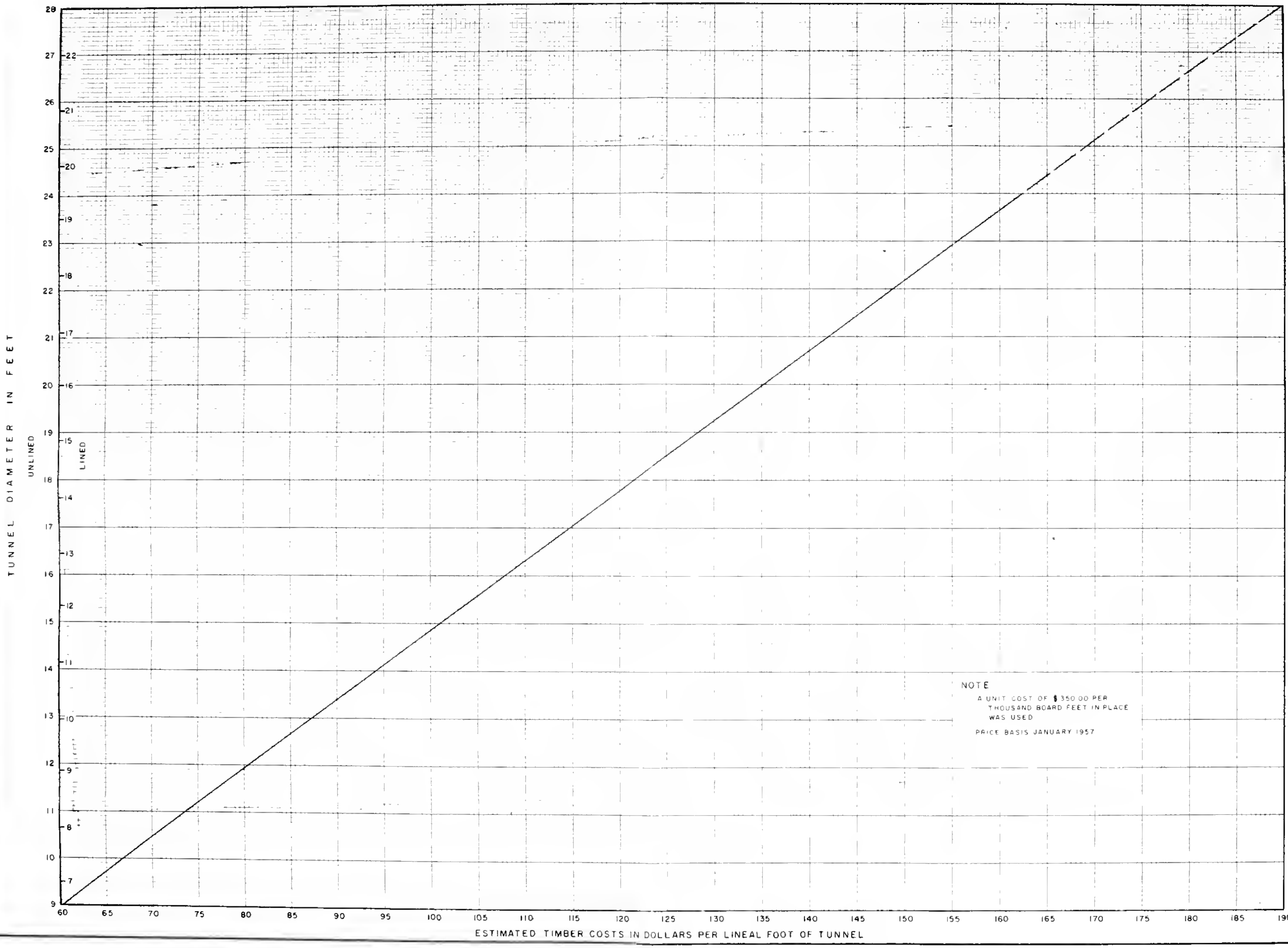

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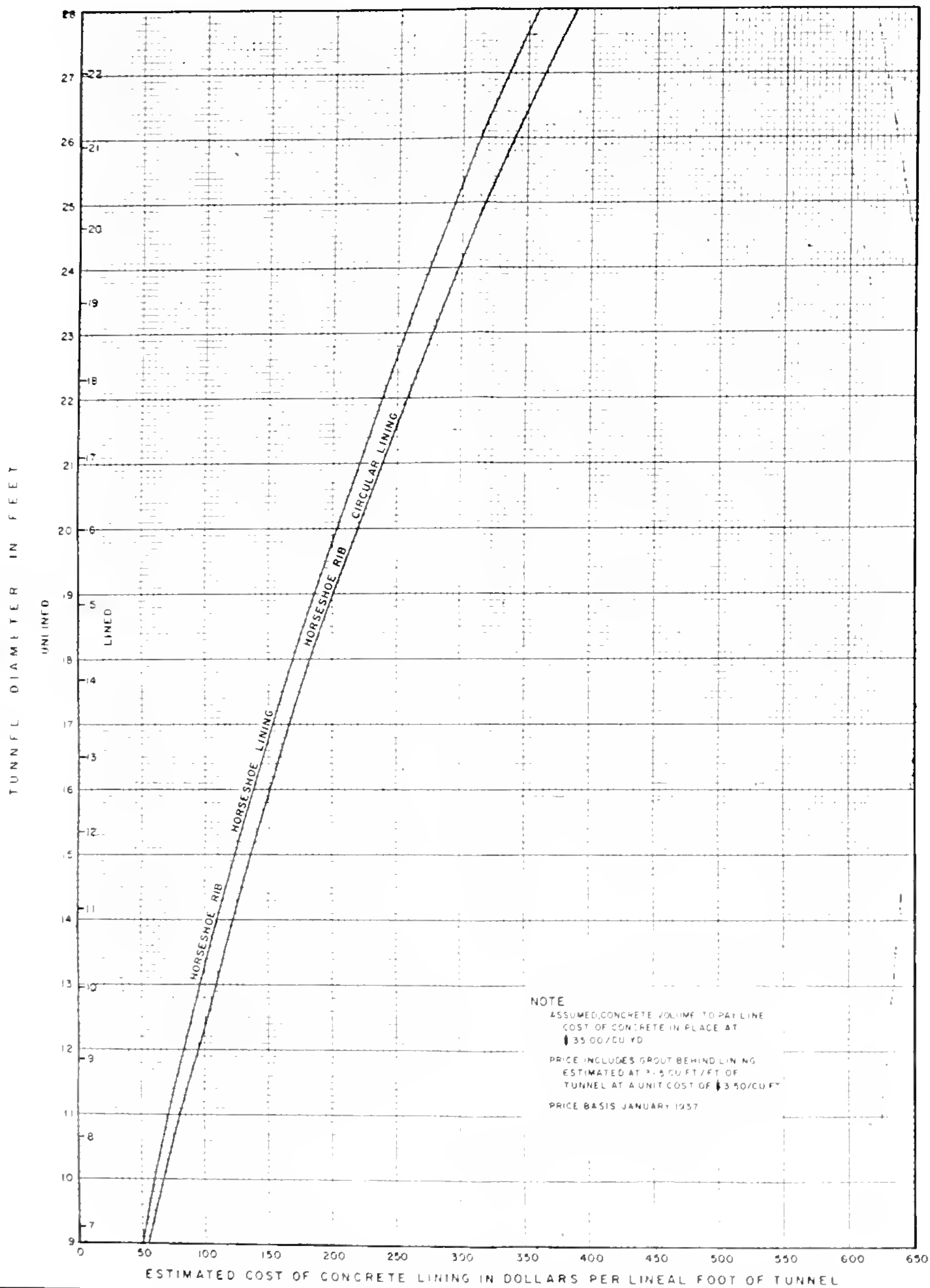
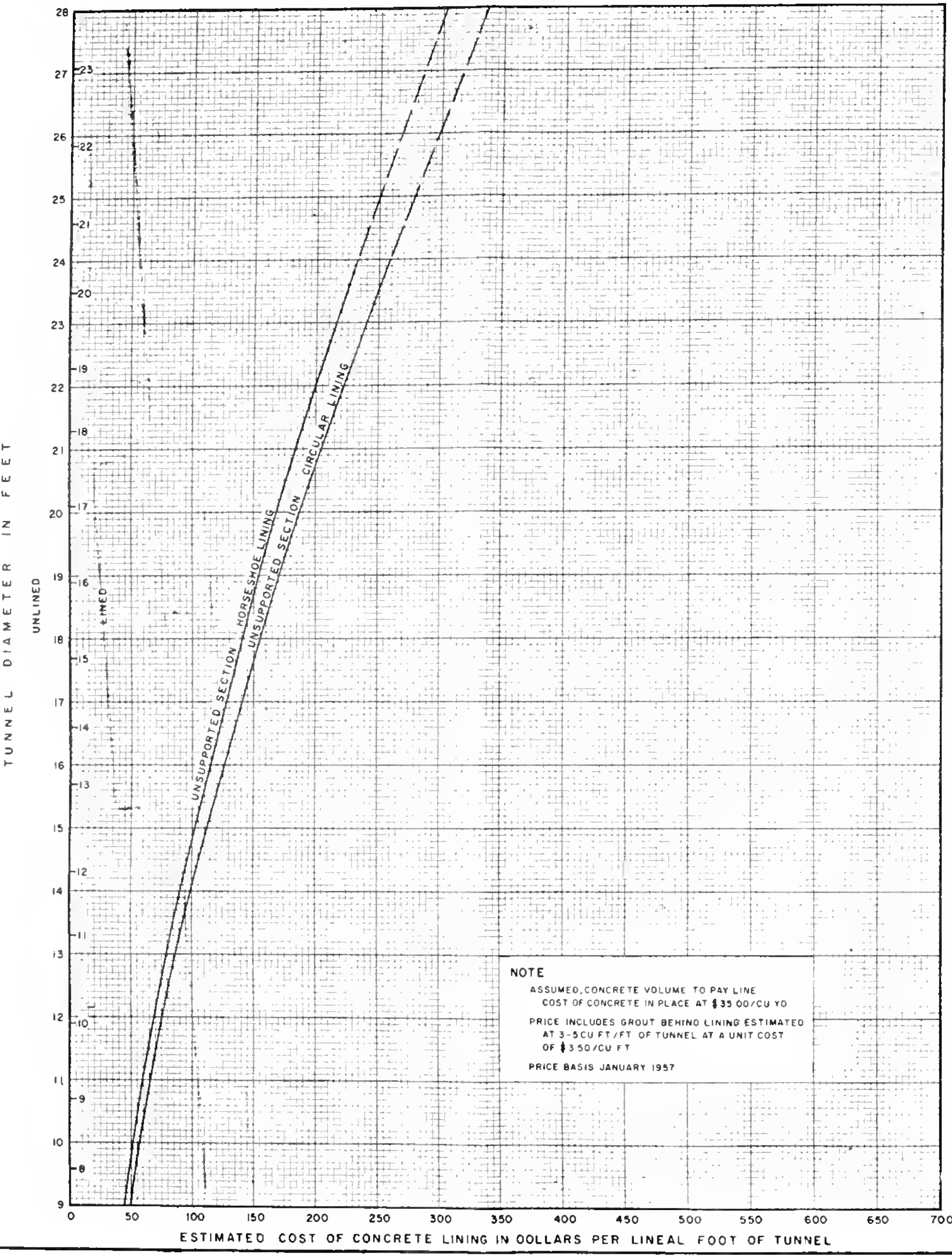
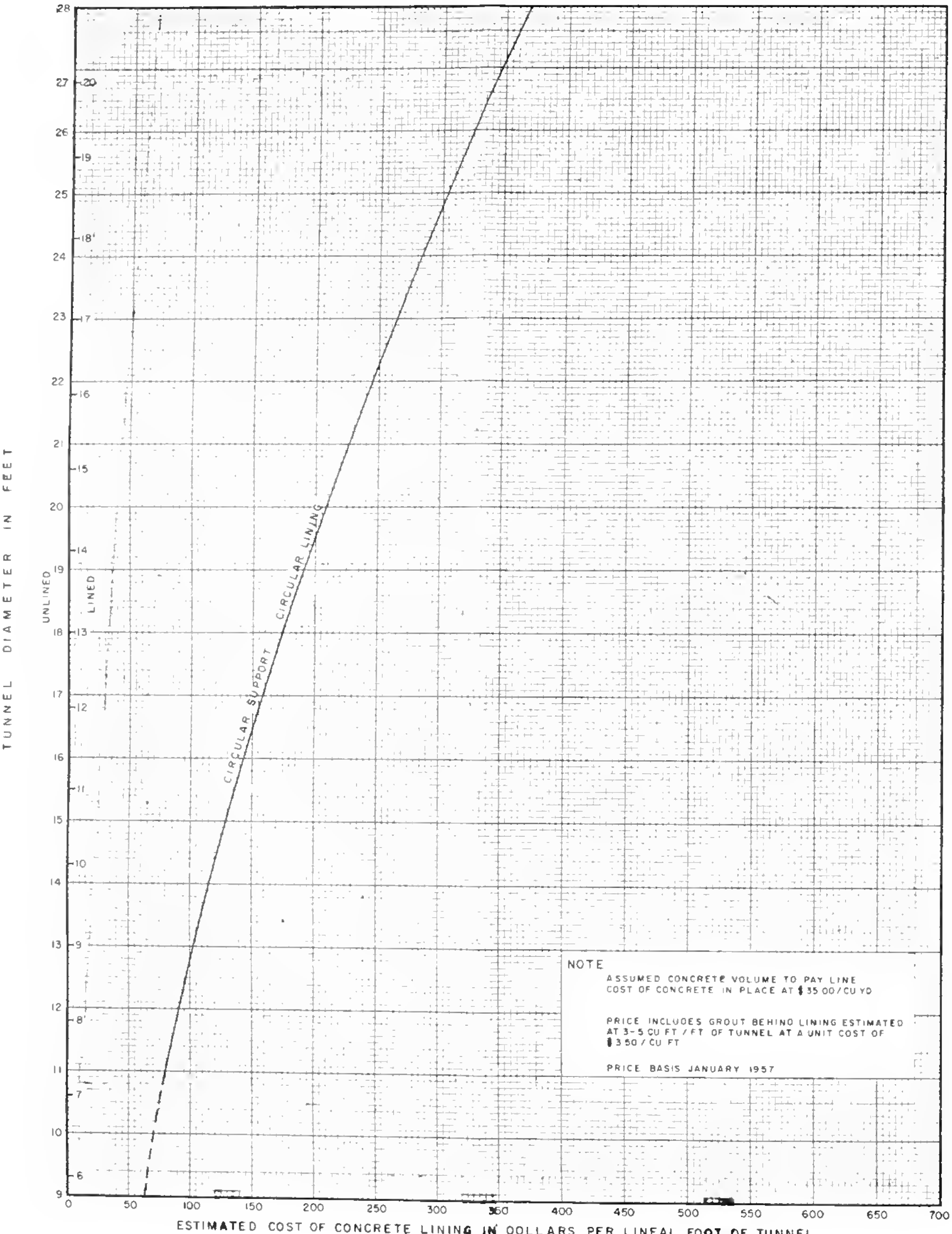


ESTIMATED COST OF CONCRETE LINING FOR TUNNELS WITH STEEL SUPPORT



ESTIMATED COST OF CONCRETE LINING FOR TUNNELS WITHOUT STEEL SUPPORT

DEPARTMENT OF WATER RESOURCES



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